Journal

of

THE ROYAL AERONAUTICAL SOCIETY

JANUARY 1959

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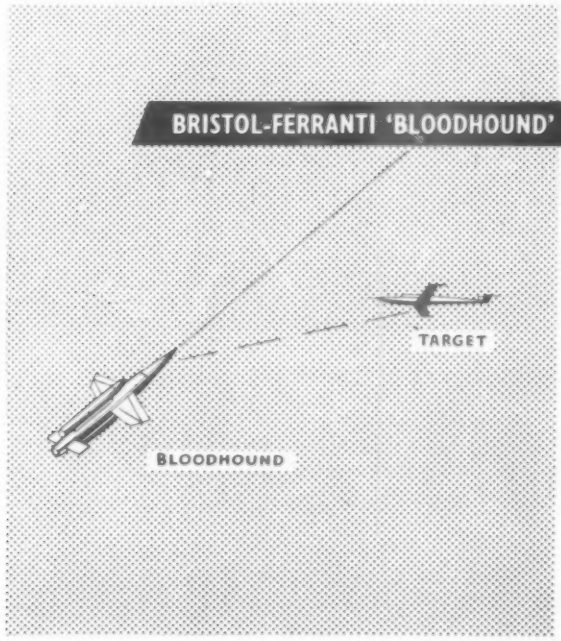

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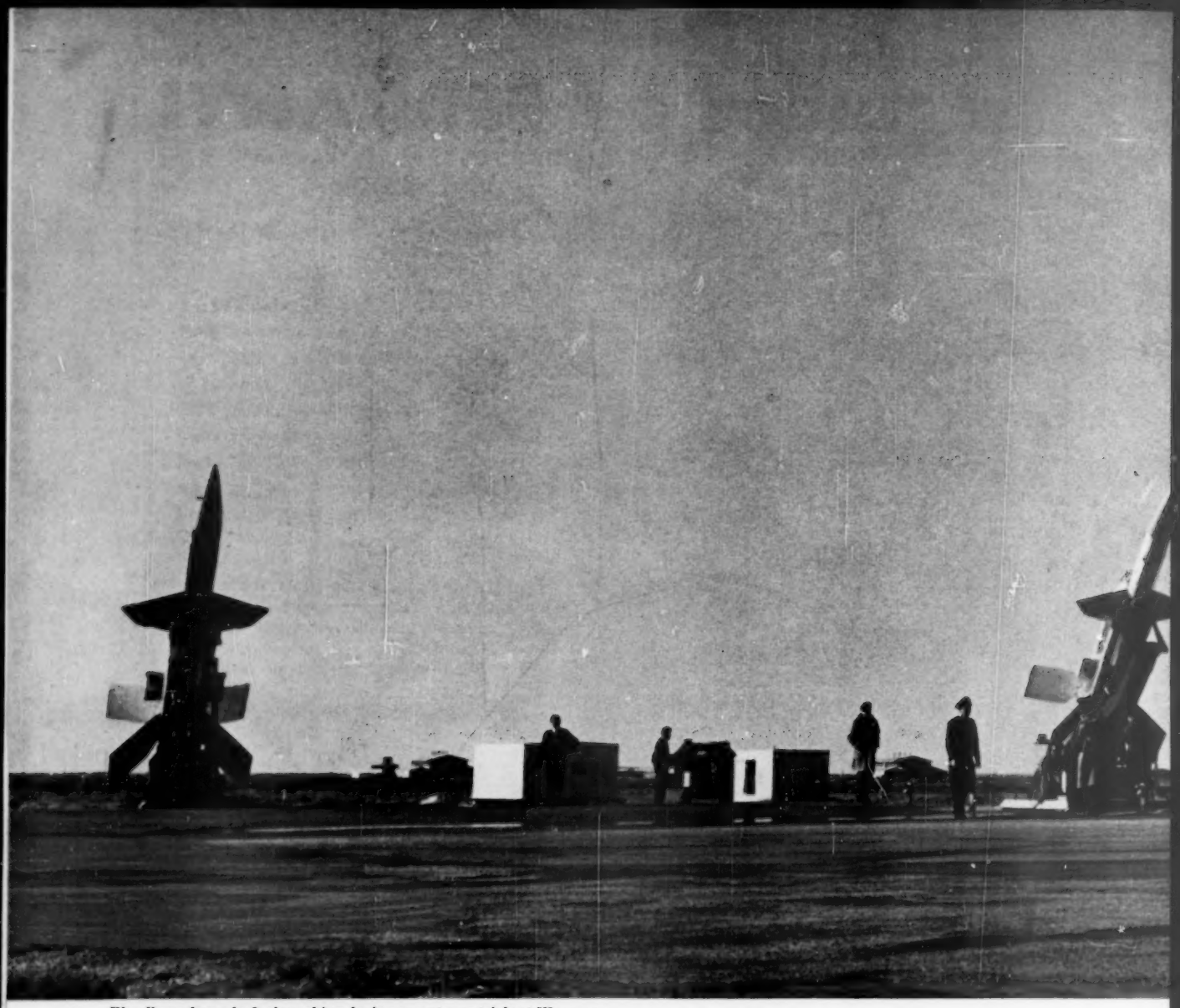

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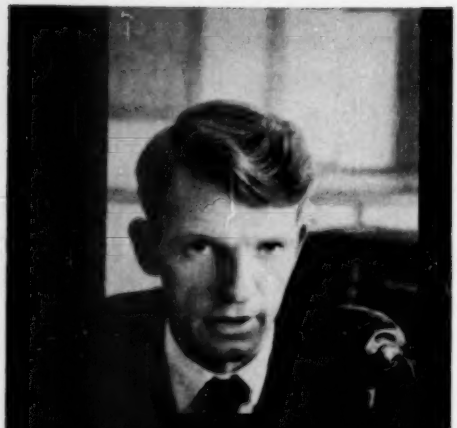
BRISTOL/FERRANTI

Bloodhound

GUIDED WEAPON SYSTEM

Weapon design and construction by Bristol. Guidance and control by Ferranti. System sales organisation by Bristol Aircraft Limited



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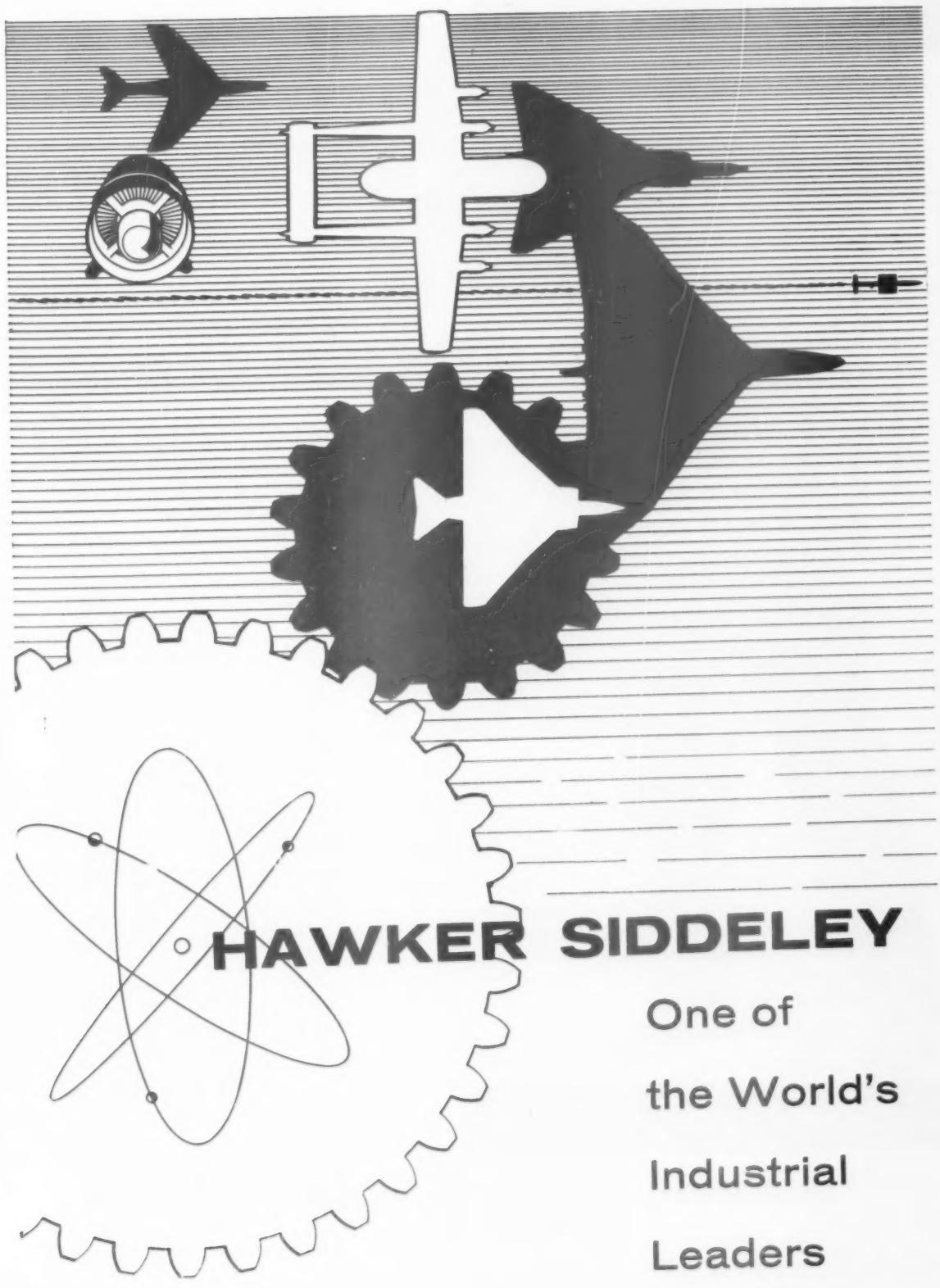
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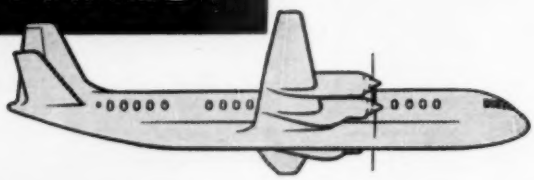

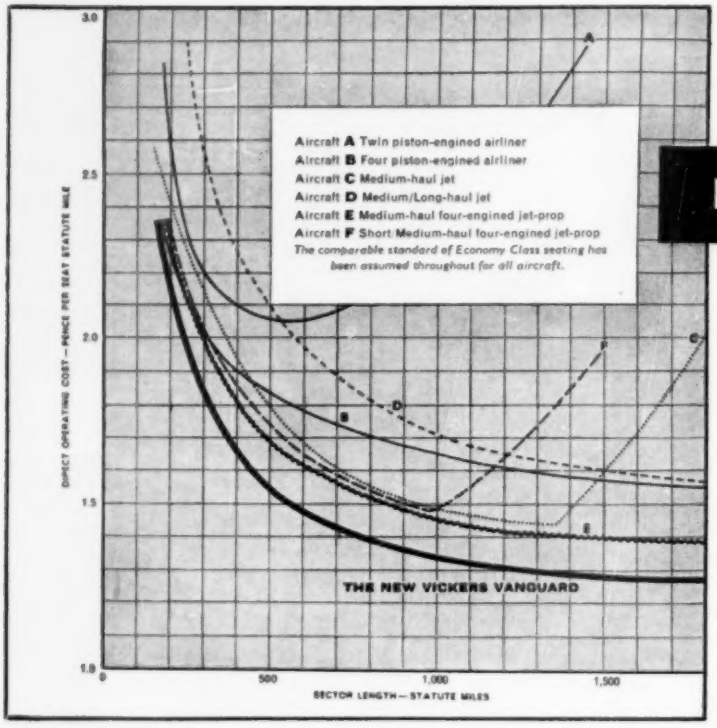

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All communication for publication in the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

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NOTICES

New Year Greeting

The President and Council of the Society send their good wishes for the New Year to all members at home and overseas.

Nominations for Fellowship of the Society

The attention of Members is drawn to the following extract from the Society's By-Laws:—

"Fellows shall comprise every person who on the 30th day of January 1950 was on the Register as a Fellow of the Society; and every person thereafter awarded the honour of Fellowship.

"Elections to Fellowship will be made annually by the Council and will be announced at the Annual General Meeting of the Society. Nominations will be initiated by the members of the Council or by any four Fellows of the Society. It is the duty of the Council to see that the honour is awarded only to persons who have attained a considerable degree of technical eminence in the profession of aeronautics."

From this, it will be seen that any four Fellows may nominate a suitable candidate for Fellowship. Nominations for 1959 must be received by the Secretary **by 31st January 1959.**

Fourth Air Transport Course—Oxford

The Fourth Air Transport Course held under the auspices of the Society will take place at Oriel College, Oxford, from 31st March to 21st April 1959 inclusive.

Brochures giving full particulars may be obtained on application to the Secretary of the Society at 4 Hamilton Place, W.1.

Acknowledgments

From the estate of the late Hon. Alan Boyle, one of the pioneers of 1910, the Society has received papers, photographs, balloon logs, etc., which are of great interest. One photograph is a 3 ft. × 2 ft. picture of the Avis Monoplane built by the Scottish Aeroplane Syndicate, which was flown by Mr. Boyle until his accident at the Bournemouth meeting in July 1910. The Council are sincerely grateful to Mrs. Boyle and her daughter Mrs. Macartney for this material.

The Council also wish to thank J. D. Field, Esq., for presenting further material, including handbooks and logs, belonging to the late C. Brian Field (*Associate*).

The Council also thank E. Somerville, Esq., of 6 Langton Avenue, Chelmsford, who, on reading of the Nash Collection in the *Evening News* has kindly presented a medal struck to commemorate the first flight over the Alps by Chavez (1910) and some postcards of the Bristol biplane of the same period.

World Congress of Flight

The First World Congress of Flight, which is sponsored by the United States Air Force Association, will be held at Las Vegas, Nevada, U.S.A. from 12th to 19th April 1959.

The Congress, which will be for "the advancement of aeronautics and astronautics," will include conferences, forums, displays and exhibitions, air and ground demonstrations and private meetings.

Details can be obtained from the European Representative for the Congress, Mr. Eugene W. Murphy, Carl Byoir and Associates International, 12 Rue Boissy d'Anglas, Paris 8.

Presidential Reception—13th February 1959

A Presidential Reception will be held in the offices of the Society on Friday February 13th from 7.30 to 10.00 p.m. Members have been sent particulars and it is hoped as many as possible will be able to be present on this occasion. Tickets may be obtained on application to the Secretary, price one guinea each, which includes Buffet Supper. The Salon Orchestra of the Royal Air Force Central Band will play during the evening (by kind permission of the Air Council).

The Presidential Address which was provisionally arranged for 15th January has been cancelled.

Branches Conference 1959

The Branches Conference will be held this year at the Bristol Branch on Friday 24th and Saturday 25th April 1959. The tentative programme is for a reception and a tour of the Britannia Hall on the Friday and a Conference and lunch on the Saturday.

News of Members

H. Adlerstein (*Graduate*), formerly with the Fairey Aviation Co. Ltd., is now a Project Designer with Sir George Godfrey and Partners Ltd., Hanworth.

W. K. Allan (*Graduate*), formerly Technical Assistant at the de Havilland Aircraft Co., has been appointed Senior Lecturer in the Mechanical Engineering Department of the Royal Military College of Science, Shrivenham.

W. H. Boyd (*Associate*) has resigned from B.O.A.C. and is now Deputy Maintenance Superintendent with West African Airways (Nigeria) Ltd.

A. B. M. Brush (*Associate Fellow*), formerly with the Lockheed Aircraft Corporation, Burbank, is now at the Lockheed Missile Systems Division at Van Nuys, California.

V. Cadambe (*Associate Fellow*), formerly with the Council of Scientific and Industrial Research, has been appointed Director, Central Mechanical Engineering Research Institute, Durgapur.

Sqn. Ldr. C. H. W. Champness (*Associate*), formerly O.C. Engineering Squadron, R.A.F. Khormaksar, has been posted to H.Q. Coastal Command for Engineer I duties.

H. Derrick (*Associate Fellow*) is now a Structures Engineer with Lockheed Aircraft, Missile Division, Sunnyvale, California.

I. F. R. Dickinson (*Associate Fellow*), formerly with Vickers-Armstrongs (Aircraft) Ltd., is now an Operations Engineer in the Special Weapons Division, Canadair Ltd., Montreal.

Group Captain A. A. Fletcher (*Associate Fellow*) has been posted as Chief Aircraft Supplies Liaison Officer at the Ministry of Supply.

Lt. Col. R. C. Fletcher (*Associate Fellow*) has been posted from the Guided Weapons Department of the Royal Aircraft Establishment to the Trials Establishment, Royal Artillery (T.E.R.A.), as Senior Technical Officer.

S. F. Follett (*Fellow*), formerly Director-General, Ministry of Supply Staff, British Joint Services Mission, Washington, has been appointed Deputy Director, R.A.E., Farnborough.

Roland A. G. Gray (*Associate Fellow*), formerly

Lecturer at the Technical School of Bristol Aero Engines Ltd., is now a Lecturer in Mechanical Engineering at the Cambridgeshire Technical College and School of Art.

W. G. HAGGITT (*Associate*), formerly Production Manager, Lan-Bar Ltd., is now Works Manager, Charles Hill and Co. Ltd., Birmingham.

E. H. HOLDER (*Associate Fellow*) has been seconded by the Ministry of Supply as Manager to the Royal Ordnance Factories, West Pakistan.

J. C. HOWARD (*Associate Fellow*), formerly a Structures Engineer with the Lockheed Missile Systems Division, is now a Mathematical Specialist with the same firm.

J. B. E. KEEBLE (*Associate Fellow*) has been posted by the Ministry of Supply to Boulton Paul Aircraft Ltd., Wolverhampton, as Resident Technical Officer.

GEORGE KENYON (*Associate Fellow*) has returned from the N.A.T.O. Defence College in Paris and resumed his duties as an Engineer I in the Directorate of Guided Weapons Production, Ministry of Supply.

Wing Commander R. H. LOWRY (*Associate Fellow*), formerly a R.C.A.F. Medical Officer in the Defence Research Medical Laboratories, is now Manager, Space Medicine Branch, Systems Management Office, Boeing Airplane Co., Seattle, Washington.

Squadron Leader G. J. MACRAE (*Associate*) has returned from R.C.A.F. College, Toronto, and is now Officer Commanding, Bomber Command Communication Squadron.

H. MAROM (*Associate Fellow*), formerly Head of the Aviation Department of the Ministry of Defence Mission at the Embassy of Israel, is now Chief Test Pilot and Development Engineer, Bedek Aircraft Ltd., Lod Airport, Israel.

W. MCGOWAN (*Associate Fellow*) has transferred to Lockheed Missile Systems Division, Sunnyvale, from Lockheed Aircraft, Burbank, as Structures Engineer.

Dr. O. P. MEDIRATTA (*Associate Fellow*), formerly Head of Guidance and Control Department, Guided Weapons, Short Brothers and Harland Ltd., is now Deputy Director (Research and Development), Directorate of Technical Development and Production (Air), Ministry of Defence, Government of India.

ARTHUR W. F. METZ (*Associate Fellow*), formerly of Armstrong Siddeley Motors Experimental Flight Section, is now Service Manager of British Motor Distributors, San Francisco.

R. W. MORRIS (*Associate Fellow*), formerly with the Lockheed Aircraft Corporation, has been appointed Manager of the Garrett Corporation at Geneva.

M. C. MUIR (*Graduate*), formerly in the Test Pilots' Office of the de Havilland Engine Co., is now in the Test Pilots' Office of Rolls-Royce Ltd., Hucknall Aerodrome.

G. R. NICOLSON (*Associate Fellow*), formerly with H.Q. Maintenance Command, R.A.F., is now engaged on work connected with the development of Guided Missiles in the Scientific Adviser's Department of the Air Ministry.

J. M. PARKINSON (*Graduate*), formerly a Technical Assistant at Short Brothers and Harland Ltd., Belfast, is now a Junior Technical Officer with Sir W. G. Armstrong Whitworth Aircraft Armaments Division, Whitley.

R. PRIZEMAN (*Associate Fellow*) has returned from the U.S.A. and is now with Industrial Administration Ltd., London.

Air Vice-Marshal G. SILYN ROBERTS (*Fellow*), formerly the Senior Technical Officer at Bomber Command, has been appointed Director-General of Engineering at the Air Ministry.

L. H. ROBERTS (*Graduate*) has left the University of Bristol and is now an Experimental Engineer with British Nylon Spinners Ltd., Pontypool.

WILLIAM H. RUTHVEN (*Student*), formerly Instrument Mechanic, R.A.F., Boscombe Down, has been appointed a Technician in the Mechanical and Structural Flight Test Section of A. V. Roe and Co. Ltd., Woodford Aerodrome.

P. S. SAUNDERS (*Associate Fellow*), formerly Chief Consultant Engineer with Louis Newmark Ltd., has joined the Senior Staff of the Instrument Wing of English Electric Co., Ltd. Stevenage.

Ing. Dipl. A. SCIBOR-RYLSKI (*Associate Fellow*) has left the London Stress Office of the English Electric Co. Ltd., and has been appointed Lecturer in Aerodynamics, Department of Aeronautical and Mechanical Design, Hatfield Technical College.

A. SEWART (*Associate Fellow*), formerly Works Manager, A. V. Roe and Co. Ltd., has been appointed Assistant General Manager (Missiles) with the same company.

D. V. SHAW (*Student*) is now Chief Development Engineer and a Director of Wemyss Woodhouse Ltd.

J. C. SIMMONS (*Associate Fellow*), formerly Deputy Head of the Technical Department of the Royal Aeronautical Society is now in the Atomic Power Department of the English Electric Co. Ltd., Whetstone.

C. W. SIMPSON (*Associate*) has left the Royal Air Force and is now a Test Pilot with Sir W. G. Armstrong Whitworth Aircraft Ltd.

P. COATES SMITH (*Associate Fellow*), formerly Contracts Engineer with Tiltman Langley Ltd., is now with Westland Aircraft Ltd. as a Projects Designer.

W. H. STEPHENS (*Fellow*), formerly Deputy Director of the Royal Aircraft Establishment, has been appointed Director-General, Ballistic Missiles at the Ministry of Supply.

D. E. TURNBULL (*Graduate*) of the British Hydrodynamics Research Association is taking up a temporary appointment with D.S.I.R. at the United Kingdom Scientific Mission in Washington, D.C. which will involve visiting Universities and manufacturers.

J. G. WALKER (*Associate Fellow*) is on a tour of Duty with the Guided Weapons Group, British Joint Services Mission (Ministry of Supply Staff), Washington, D.C.

D. J. WRIGHT (*Associate Fellow*), formerly with Export Packing Services Ltd., is now Chief Engineer of Barrett Packaging Ltd., Grantham.

DIARY

LONDON

8th January

MAIN LECTURE—Safe Mechanisms. R. Hafner. The Institution of Mechanical Engineers, Birdcage Walk, S.W.1. At 6 p.m. (Tea at 5.30 p.m.)

13th January

LECTURE—Stress Corrosion—The Engineer's View. P. H. Wall, Library, 4 Hamilton Place. 7 p.m.

27th January

LECTURE—Some Aspects of the Engine Noise Problem. P. Lloyd. Library, 4 Hamilton Place. 7 p.m.

5th February

MAIN LECTURE AT HATFIELD BRANCH—The First Halford Lecture. J. L. P. Brodie. Main Hall, Hatfield Technical College. 6.15 p.m. Followed by the Branch Annual Dinner.

12th February

MAIN LECTURE★—Earth Satellites. W. H. Stephens. Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

13th February

PRESIDENTIAL RECEPTION. 4 Hamilton Place. 7.30 p.m. to 10 p.m. **See special notice.**

17th February

LECTURE—Engine Starting Systems. R. H. Woodall. Library, 4 Hamilton Place. 7 p.m.

19th February

LECTURE★—Theoretical Studies of Guided Missile Control Systems. E. G. C. Burt. Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

★ **Arranged by the Committee of the Guided Flight Section.**

24th February
LECTURE—The Flight Development of an Aircraft Before and During its Operation. Dr. A. E. Russell, C. Abell and Dr. E. J. Warlow-Davies. Library, 4 Hamilton Place. 7 p.m.

BRANCHES

12th January

Henlow—Vertical Take-Off and Landing. D. Keith-Lucas. Building 62, R.A.F. Technical College. 7.30 p.m.

13th January

Boscombe Down—Experiences on the Trans-Antarctic Expedition. Sq. Ldr. J. H. Lewis. Lecture Hall, A. & A.E.E. 5.45 p.m.

14th January

Brough—Young People's Christmas Lecture. Newland High School, Cottingham Road, Hull. Afternoon.

Chester—Development of the Civil Avon Engine. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Christchurch—The Rotodyne. Dr. G. S. Hislop. King's Arms Hotel. 7.30 p.m.

Manchester—Nuclear Reactors for Power Production. T. M. Greenlees. Reynolds Hall, College of Technology. 7.30 p.m.

15th January

Glasgow—Graduates' and Students' Section—Question Night and Film Show. Engineering Department, University of Glasgow. 7.30 p.m.

16th January

Cambridge—Lecture by Dr. N. A. de Bruyne. No. 1 Lecture Theatre, Cambridge University Engineering Laboratories. 8.15 p.m.

20th January

Luton—Junior Paper Evening. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

22nd January

Bristol—Guided Missiles (1). Filton House. 6 p.m.

Isle of Wight—Nuclear Propulsion of Aircraft. J. V. Dunworth. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

Southend—Modern Aircraft Production Methods. Labour Hall, Boston Avenue. 7.30 p.m.

26th January

Halton—The Beverley in Service. Gp. Cpt. F. C. Griffiths. Branch H.Q., R.A.F. Halton. 6.45 p.m.

28th January

Southampton—Recent Developments in Noise Suppression. Prof. E. J. Richards. Institute of Education, University of Southampton. 8 p.m.

Weybridge—Film Show. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

29th January

Belfast—Scientific Research with High Altitude Rockets. Dr. E. B. Armstrong. Lecture Hall LG8, David Keir Building, The Queen's University. 7. p.m.

Bristol—Guided Missiles (2). Filton House. 6 p.m.

Preston—Flying Boats. M. J. Brennan, Hewitt Lecture Room, Lythan. 7.30 p.m.

30th January

Chester—Annual Dance. Quaintways Restaurant.

2nd February

Derby—Performance Problems in Large Rocket Engines. S. L. Bragg. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.

Glasgow—Graduates' and Students' Section—Tropical Trials of the Scottish Aviation Twin Pioneer. J. Chalmers and Captain J. Blair. Scottish Aviation Technical School, Prestwick. 7.30 p.m.

Henlow—Presidential Address. L. H. G. Sterne. Building 62, R.A.F. Technical College. 7.30 p.m.

3rd February

Boscombe Down—The Training of Soviet Engineers. E. G. Sterland. Lecture Hall, A. & A.E.E. 5.45 p.m.

Luton—Systems Simplified. J. Wotton. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

4th February

Brough—Production of the P.1. T. O. Williams. Small Lecture Hall, Royal Station Hotel, Hull. 7.30 p.m.

Christchurch—Lecture in conjunction with the British Association for the Advancement of Science. Kings Arms Hotel. 7.30 p.m.

Gloucester—Supersonic Propulsion. R. R. Jamison. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

London Airport—Power Plants of the Future. A. A. Lombard. Lecture Hall, Fairey Aviation Co. Ltd., Hayes. 6.15 p.m.

5th February

Bristol—Guided Missiles (3). Filton House. 6 p.m.

Hatfield—MAIN SOCIETY LECTURE. The First Halford Lecture. J. L. P. Brodie. Main Hall, Hatfield Technical College. 6.15 p.m. Followed by the Annual Dinner.

Isle of Wight—Vertical Take-Off Aircraft. Prof. E. J. Richards. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

Swindon—Technical Education. Prof. A. R. Collar. The College, Victoria Road. 7 p.m.

9th February

Cambridge—Film Show. No. 1 Lecture Theatre, Cambridge University Engineering Laboratories. 8.15 p.m.

Glasgow—Pilcher Memorial Lecture—History of Stability and Control. Dr. A .W. Babister. Room 24, Royal College of Science and Technology. 7.15 p.m.

Halton—Flying the Fairey Delta 2. L. P. Twiss. Branch H.Q., R.A.F. Halton. 6.45 p.m.

11th February

Chester—The History and Development of Manchester's Airports. G. A. Harvey. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Manchester—Flight Corridor Research. J. E. Allen. Reynolds Hall, College of Technology. 7.30 p.m.

Reading—Noise. Prof. E. J. Richards. Canteen, Western Manufacturing Ltd. 6.15 p.m.

16th February

Henlow—Student Members Papers. Building 62, R.A.F. Technical College. 7.30 p.m.

18th February

Southampton—Rockets and Interplanetary Flight. W. N. Neat. Institute of Education, University of Southampton. 8 p.m.

Weybridge—Aircraft Carriers. J. C. Lawrence. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

19th February

Bristol—Junior Committee Lecture—Cosmic Radiation. Prof. C. F. Powell. Filton House. 6 p.m.

25th February

Bristol—C.A.A./A.R.B. Lecture. Future Safety Requirements in Air Transport. Filton House. 6 p.m.

Christchurch—Navigation Aids. G. E. Beck. Kings Arms Hotel. 7.30 p.m.

Hatfield—Development of the P.1. Aircraft. F. W. Page. de Havilland Restaurant. 6.15 p.m.

Preston—Operational Problems in Supersonic Flight Testing. R. P. Beamont. R.A.F. Association Hall, Preston. 7.30 p.m.

26th February

Belfast—Noise and its Effects on Aircraft Structures. M. O. W. Wolfe. Lecture Hall LG8, David Keir Building, The Queen's University. 7 p.m.

Isle of Wight—Development of Submarines. R. N. Newton. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

Southend—Aircraft Electrical Installations. G. G. Wakefield. Labour Hall, Boston Avenue. 7.30 p.m.

Elections

The following is a list of new members and transfers of membership of the Society.

Associate Fellows

Arthur Akers (*from Graduate*)
Richard Douglas Archer (*from Graduate*)
Thomas Frank Arlotte (*from Graduate*)
Beryl Mary Bigg (*from Graduate*)
David Alan Hughes Bird (*from Graduate*)
Raymond Alfred Arthur Bryant (*from Companion*)
Michael Lawrence Camp (*from Graduate*)
John Alfred Chilman
Roy Edgar Clement (*from Graduate*)
Anton Coles (*from Student*)
Clifford John Thomas Coombs (*from Graduate*)
Donald Diamond (*from Associate*)
Alfred John Wilson Dick (*from Graduate*)
Edward Derek Dixon (*from Graduate*)
Alan Michael Dobson
Dane Henry Donaldson
Lee Joseph Fischer
Kenneth Allan Fisk (*from Graduate*)
Maurice Vivian Fox-Strangways
Thomas Leonard Hall (*from Graduate*)
Jean Mathieu Hubertus Heines (*from Companion*)
Rowland Hill
Charles Neville Jones (*from Graduate*)
Edward Robert Albert Landers (*from Student*)
David William Lane
Peter David Royton Luscombe (*from Graduate*)
Nigel John McKellar (*from Graduate*)
Peter Laurence Manley
Kenneth Eric Monger
Francis John Morley (*from Graduate*)
David Ronald Puttock (*from Graduate*)
Grahame Charles Quigg (*from Graduate*)
John Shackell (*from Graduate*)
John Denman Sibley (*from Graduate*)
Arthur Edwin Smith
David Harry Smith (*from Graduate*)
Alexander Rodger Sturgeon (*from Associate*)
Madhusudan Sripad Tatke
Ronald Daniel Teire
Patrick Graeme Tweedie
John Victor Vint (*from Graduate*)
Denis Sword Whitehead (*from Graduate*)
William Gerald Williams (*from Graduate*)
Denys William Wright (*from Graduate*)

Associates

Leopold Clifford Balderamos
Charles Stanley Bell
Eric James Cockell
Robert Percival Craigen
David Cuthbertson
Thomas Edgar Ellen
Trevor John Ford (*from Student*)
John Harman
Eric Leonard John Hughes
Eric Alexander Robert Jolly (*from Student*)
Jack Ludford
John Hugh McFarlane
Frederic Louis Hippolyte Marie Ghislain Meeus
Peter William Norton
Sydney Lionel W. Page
Colin Pimley
Keith Lionel Norman John Trow

Graduates

Rose Dunstan Barkla
David Michael Fraser Bright
Robert Armstrong Brown
Eric John Bucklow
Arthur Henry Comber
Christopher Maxwell Darby
Bruce George Edward Allen Foster (*from Student*)
Arthur Eric Donald Gunn
John Gordon Scott Norman (*from Student*)
Martyn Stanley Pressnell
Ian Thompson
Michael Richard Louis Thurner
John Albert Wallis
Brian Laurence Weeks
Ian Winterbottom (*from Student*)

Students

David William Atkins
Robin Edward Hume Austen
John Barton
Herbert Richard Beattie
Alan Terence Boyd
David William Brittain
John Albert Coath
David Francis Colbeck
Zenon Walter Fedun
Alan Charles Finch
Michael Thomas Hards
Michael Harding Harries
Michael Gerald Couzens Hills
John Richard Hoddinott
Chung Tow Huey
Alan Sidney Humphreys
William Peter Jennings
Robert Eric Lee
Brian William Loughridge
Anthony McCabe
Michael Vivian Stuart Mann
John Wyllie Nicol
Ian Thomas Nicoll
Kenneth Edward Odbert
Robert Brian Page
Jimmie Terence Pocock
Peter John Ratcliffe
Frederick Dalziel Robson
Geoffrey Norman Sage
Brian Sellers
Geoffrey Raymond Hartley Slack
John Stanley Slavik
Leslie John Smith
David Thomas Sparham
Peter Gordon Stevens
Robert George Waller
Jeremy Michael Yates
Mushtaq Ali Zamindar

Companion

Michael Gabriel Sherry (*from Graduate*)

Studentships at the Royal Military College of Science

The Royal Military College of Science, Shrivenham, offers a number of civilian studentships to prepare students for London University degree of B.Sc. (Special) in Chemistry, Physics or Mathematics, or B.Sc. (Engineering). The Studentships are specially designed for training young scientists for Government Research Establishments and boys to whom awards are made are expected to join the Scientific Civil Service when they have taken their degrees.

The College is residential and the Studentships cover tuition and examination fees and an allowance of £355 a year. No Means Test is imposed. Candidates must be under 22 years of age on the 1st October of the year of entry unless they have completed their National Service, when they must be under 24 years.

Application forms and further information may be obtained from the Ministry of Supply, Est. 3(R)3, Room 512, The Adelphi, Strand, London W.C.2.

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Journals. with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Members are asked to be certain that the address to which they want their Journals sent is the same on their letters to the Lewes Press and to the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals are available from the Offices of the Society at 13s. 6d. each (including postage *in the United Kingdom*).

Changes of Address or Appointment

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters) Grade of Membership
New Address (in block letters) Old address

New appointment.—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

GENERAL MEETING OF THE SOCIETY

Increased Subscriptions

The following is the report of the General Meeting of the Voters of the Society, held in the Library of the Society, 4 Hamilton Place, London W.1 on Wednesday 3rd December 1958 at 6 p.m. The President, Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S. presided.

THE PRESIDENT: The Secretary reports that we have a quorum, so I shall ask him to read the Notice convening the Meeting.

THE SECRETARY:

"NOTICE IS HEREBY GIVEN that a General Meeting of the Voters of the Society will be held in the Library of the Society at 4 Hamilton Place, W.1 on Wednesday the 3rd day of December 1958 at 6 p.m. for the purpose of considering and if thought fit of passing the following resolution proposed by the Council of the Society.

"That as from the 1st January 1959 the rates of annual subscription for the respective grades of the Society be as follows:—"

		Home	Abroad
		£ s. d.	£ s. d.
Fellows		8 0 0	7 0 0
,,	(aged 65 and over)	5 0 0	4 0 0
Associate Fellows		6 0 0	5 0 0
,, ,,	(aged 65 and over)	4 0 0	3 0 0
Associates†		5 0 0	5 0 0
,,	(aged 65 and over)	3 0 0	3 0 0
Graduates	(aged 21-25)	2 10 0	2 10 0
,,	(aged 26 and over)	3 0 0	3 0 0
Students	(aged under 21)	1 10 0	1 10 0
,,	(aged 21 and over)	2 0 0	2 0 0
Companions	(with Journal)	4 0 0	4 0 0
,,	(aged 65 and over)	3 0 0	3 0 0
,,	(without Journal)	2 10 0	2 10 0
Founder Members		—Nil—	—Nil—

† NOTE—Any Associate who joined before 1st October 1947, and has elected not to receive the JOURNAL will pay a reduced subscription of £3 10s. 0d.

ENTRANCE FEES	£ s. d.
Fellows	10 0 0
Associate Fellows	6 0 0
Associates	3 0 0
Graduates	2 0 0
Students	—Nil—
Companions	—Nil—

TRANSFER FEES	£ s. d.
Associate Fellow to Fellow	4 0 0
Associate to Associate Fellow	3 0 0
Graduate to Associate Fellow (or Associate)	2 0 0
Student to Associate Fellow	4 0 0
Student to Associate	3 0 0
Student to Graduate	2 0 0
Companion to Associate Fellow	4 0 0
Companion to Associate	3 0 0

THE PRESIDENT: You are all aware of the Resolution. May I ask if there are any questions on it?

DR. A. KING (*Associate Fellow*): Mr. President, I should like to make one enquiry. In considering this proposal, have the Council taken into account the possibility of not levying the same subscriptions on provincial Members since they do not have the same facilities as Members in London and the Home Counties? I note that provision is made for Members who are abroad; that is an obvious case. It would appear that provincial Members do have something to say on this, but obviously they cannot attend meetings such as this. I think it may well be true to say that I, apart from one or two notable exceptions, am about the only Member from the provinces here, and I feel that on behalf of those people I ought to raise the point.

THE PRESIDENT: It seems to me that your point has two parts: firstly, whether the Council have considered the provincial Members as a special case; and, secondly, the position of the provincial Members in a Meeting of this kind.

Let us deal with the second question first. The conditions for a Meeting of this kind are set down in our By-Laws and this Meeting is called—I think the solicitor will confirm this—fully in accordance with the By-Laws.

As regards the question of a differential on subscriptions, this has often been raised, but the Council are not of a mind, anyway at this time, to make such a suggestion. I think that is probably the most I can say. Perhaps the Treasurer would like to add something.

THE HONORARY TREASURER (Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S.): Mr. President, I think there is this

point that most of the Members in the provinces are Members of Branches each of which has a lively and effective programme. I would say that although they do not have all the benefits of the events in London, they have a very active life and a great participation in the general work of the Society.

THE PRESIDENT: In addition to that, the Branches are all subsidised from the funds of the Society.

DR. KING: May I just come back on one point? I am not absolutely certain of the figure of the grant made to the Branches. If I remember correctly—it is some weeks since I read the figures—it is a fairly small amount. In fact, I think it is true to say that the Branches are in effect almost self-sufficient; I am open to question on that point. Therefore, I do not think people will be quite willing to accept the argument which has been put before us.

An additional point is—and this is not necessarily my own view, Sir, I am just reporting something which I have heard mooted by several other people—that an increase in membership fees of this nature may well tend to make us think twice about renewing our membership. I think this is obviously a very real problem concerning especially those people who have other qualifications and who have the amenities of perhaps the library of a company and so on, and the possibility of joining a Branch for five shillings. This does not mean to say that these people have the right spirit towards the Society but this is not a point which is relevant at this particular juncture. This may well influence matters, and therefore I would like to leave it at this point.

THE PRESIDENT: Are there any other points which people wish to make?

WING COMMANDER A. L. FUSSELL (*Associate Fellow*): Mr. President, I would like to ask for the views of the Finance Committee. In the pamphlet here they have made a general case for an increase. From the way I read this, they have not made a case for the specific increases which they have proposed. They must have had some general objective in mind. Was it to make us self-supporting or, perhaps, was it to build up the reserve fund for the future? Could we please be told what determined the amount of the increases?

THE PRESIDENT: The question asked was "what is the basis on which the new scale has been determined?"

THE HONORARY TREASURER: The actual basis is that we require more money to pay for the Society's activities. The subscriptions were last fixed in 1947, but since then the value of the pound has dropped: it is only worth about 14s. today. The Council examined the subscriptions for each grade and considered the figure to which each could be fairly raised. As a Fellow is the top grade we thought he should pay the most. We have suggested £8 which is an increase of £2 15s. 0d., just over a shilling a week for the home Fellow. The Fellow abroad is to pay an increase of £2 16s. 0d. as he only paid £4 4s. 0d. before. The Associate Fellow at home is to pay £6 which is an increase of £1 16s. 0d., and the Associate Fellow abroad is to pay an increase of £1 17s. 0d. The Associate has always paid the same as the Associate Fellow abroad and so he goes up to £5 which is an increase of £1 17s. 0d. Graduates are to be put up from £2 2s. 0d. to £2 10s. 0d. which is an increase of 8s. Graduates over 26 are to be put up from £2 12s. 6d. to £3 which is an increase of 7s. 6d. Students under 21 were not affected at all in 1947; they have always paid the same rate of £1 1s. 0d. We suggest £1 10s. 0d., the difference being only 9s. Students over 21 are to be put up from £1 11s. 6d. to £2 which is an increase of 8s. 6d. Companions are to be put up from £3 3s. 0d. to £4 which in an increase of 17s.

In other words, we have tried to spread the increase fairly over the whole subscriptions, considering, as I suggest, that the value of the £1 in 1947 is worth 14s. today. We therefore have the obvious need for increased subscriptions. It is a fact that whereas until about five years ago the subscriptions paid for 82 per cent of the total cost of running the Society, they are now only paying for 64 per cent. The whole of the difference is made up from voluntary subscriptions by firms, the S.B.A.C., the Ministry of Supply, and so on. We cannot expect these outside parties to continue their generosity to the Society if the Members themselves do not appear to be pulling their weight. There is no particular magic about any of these figures. It seemed to us the best way of doing it.

THE PRESIDENT: To summarise the reply, the changes will repair the ravages of inflation. We have also taken the opportunity of turning the figures from guineas to pounds in the process.

THE HONORARY TREASURER: It is interesting to look at the subscriptions of other societies. The Institution of Civil Engineers pay £11 or £8 if they are outside a 20 mile radius. The Members and Companions of the Institution of Mechanical Engineers pay £7 5s. 0d. The Members and Companions of the Institution of Electrical Engineers pay £7. The Members and Associates of the Institution of Structural Engineers pay £8. The Institute of British Architects pay £12. Graduates of the Institution of Civil Engineers pay £5. Graduates of the Institution of Mechanical Engineers aged 20 to 24 pay £2 10s. 0d., Graduates aged 24 to 29 pay £3 5s. 0d., and Graduates aged 29 to 35 pay £4 5s. 0d. Graduates under 26 in the Institution of Electrical Engineers pay £2 7s. 6d., Graduates aged 26 to 28 pay £3 5s. 0d., Graduates aged 28 to 35 pay £4 5s. 0d. Graduates of the Institution of Structural Engineers aged under 35 pay £3 10s. 0d. and Graduates over 35 pay £4 10s. 0d. Therefore, again, we are a little under rather than equal to the average of the other societies.

THE PRESIDENT: May I ask if that satisfies you?

WING COMMANDER FUSSELL: I take it that the differential has been chiefly determined by the excessive rate of inflation. May I ask, Mr. President, if anything in the nature of a trial balance has been done to indicate what the finances of the Society should be at the end of the next financial year, assuming membership remains the same? I am trying to determine whether we are likely to have a large surplus and therefore be able to undertake additional commitments or whether we are just keeping abreast of inflation.

THE PRESIDENT: The answer is "yes." We have struck a trial balance and we have gone into what can be done with the extra funds.

THE HONORARY TREASURER: Assuming every existing Member continues his subscription at the higher rate, the extra income will be just over £13,000 a year. However, it is not £13,000 into the pocket, because, as shown in the circular which has been issued, there will be increased expenses. We are expecting a drop in this current year of £3,000 in JOURNAL advertising alone. We have derived a rent from 8 and 9 Hamilton Place of £1,500 for several years. This tenancy expires at the end of the year, but we are hoping to extend the lease for a short period, but that is by no means certain. The lease of 4 Hamilton Place, which is in negotiation now up to 2004—may not include numbers 8 and 9 Hamilton Place. So it would seem we shall lack the £1,500 a year.

There was nothing we could do regarding an Education Officer whom we have been hoping to appoint for the past year, because we could not afford enough money.

I reckon that, assuming all the Members continue their subscriptions, we shall obtain an extra revenue of £13,000. We shall, however, only have a surplus to the extent of £5,000 or £6,000 a year; I think we ought to have a small surplus year by year, to build up increasing funds for a lecture hall, and so on. We should try to provide a little extra each year.

THE PRESIDENT: To add to that, I think the Council take the broad view—I certainly do as a person and as a Member of the Council—that the Society has a widening field of interest in these days. The Guided Flight Section is being extremely successful, there are moves in astronautics, and a general widening of the activities with increasing demands for the specialised services of the Society which we must, in the interests of our Members, attempt to follow vigorously. However, at a time when certain sources of revenue, by nature of the general situation, will become more restricted, clearly the Members face a decision in principle as to whether the ravages of inflation and the other ravages from the general situation are to work to the disadvantage of the Society—that is whether the Society's services shall be reduced which would I think, be very bad indeed at this time—or whether they are to face these modest increases to hold the prestige of the service of the Society at the level appropriate to a great profession.

Of course, one adds to that—it was coincidental in time and certainly had nothing to do with motivating our Resolution at all—the fact that the Treasury and Income Tax Authorities have suddenly become very benevolent. The net result of this is that the Member will pay less, in most cases, than he has paid in the past.

I would, however, like to make it clear that the question of the subscription level which was appropriate had been wholly reviewed and decided before the Inland Revenue indicated their position.

Have we answered you well enough, Sir? Are there any other points?

MR. R. W. PRIZEMAN (*Associate Fellow*): Mr. President, you have mentioned the expanding need for the Society's services. This Document tends to look at this present financial problem on a very short-term basis. I speak as one who has left the Aircraft Industry, I think even that, therefore, colours my attitude but I feel that even the most optimistic Member of the Society must agree that the halcyon days of the aircraft industry have passed. This is particularly evident this week from the interest which has been taken in the Commons, and the comments of Mr. Woodley, of Vickers, appearing on television last night; various other factors seem to be underlining the decreasing part which the aircraft industry might play in the future economy of this country. I think the majority of technical and trade people, within what we term the aircraft industry, even today are, in fact, engaged in work which is not by any stretch of imagination, aeronautical. I feel that, today, and even more in the future, the possession of membership of the Mechanical and Electrical Engineers is more important to the members of the so-called aircraft industry than the membership of this Society.

I wonder if the Council have investigated what the proper place of the Society will be in, say, ten years. Pure aeronautics does seem to make a small demand. The Institute of the Aeronautical Sciences have very vigorously embraced space travel within their confines, and the Society here has not been quite so vigorous in making it plain that it does wish to represent the official institution for fostering further development in this country. I wonder what the Council's attitude is with regard to the future place of the Society?

THE PRESIDENT: The first thought which occurs to me is that one must remember that for about the first half of the Society's life there was no aircraft industry of any kind. Therefore, the state of health of the aircraft industry is not the only criterion by which we judge the effectiveness of a Society of this kind. I think it is true to say that when all the ravages are over—the ravages which you so clearly described—the aircraft industry will probably be larger than it was even as late as 1949. Therefore, I take the view that any suggestion that the Royal Aeronautical Society, which has been going now for 92 years, shall suddenly come to a stop is almost certainly falsely based. We plan on the basis that the Society has been in being nearly a century and will be in being for more than another century.

You then asked what view do we take about the situation in ten years' time. That is too difficult to answer with any clarity. But broadly, we take the view that it is our duty to preserve the Society in a state of professional health, following the needs and interests of its membership; this leads to your point on what is called "space." Of course, we have, perhaps with traditional British conservatism, been less outspoken than our American sister. However, if you look at the lecture programme of the Society you will see that it contains a fair percentage of astronautical material, and the Council at its last meeting passed a resolution that that should be extended and special arrangements made to foster it.

I think a straight answer to your question is that it is the intention of the Society to follow the interests of its Members and provide a meeting ground for those Members. I should like to say, however, that we do not regard ourselves as a monopoly. We are a Chartered body for our Members but we would not certainly take the view that we wish to enter a battle in order to be the only people who did these things. We have never done that. With regard to the aero-engine we have always made arrangements with the Institution of Mechanical Engineers, whom we recognise have an interest in the matter, suitable to both parties.

The Royal Society is a leading figure in Space. There is the British Interplanetary Society. We do not take the view that we are embarked on a battle for exclusiveness, but we do take the view that it is our duty and intention to follow the interests of our Members. I can, I think with confidence, face that part of your question by saying, "Yes, that is to be looked at."

As regards the general question, it is a matter of opinion what the state of aviation may be in ten years' time. I do not know. What I am quite sure about is that we should foster the continuing existence of the Royal Aeronautical Society, we should widen its interests to suit its Members and we should carry out its professional tasks at least to the required standard.

In times of difficulty this may eventually be the rock on which everything will rest. We feel we are entitled to come to the membership to support us particularly through a time of difficulty. We go on to say that these changes of subscriptions for which we are asking—the Treasurer has defended the case as clearly as possible so I will not do it again—are not excessive; they do no more than cover the inflationary rise. We have if anything, compared with other bodies been late in coming to our membership and pointing out that there has been an inflationary rise of which most people are aware. Most bodies have done it long ago. You may say it is a tribute to the care which the Council took over these things that they have preferred to delay rather than to come quickly. I do not know whether I have answered you; I have done my best.

MR. PRIZEMAN: I am heartily in favour of subscriptions being increased; I have always found the services of the Society excellent. To come back to what might seem a general question and tying it in with this Document, do you not think that as this Society has existed, as you said, for nearly a century without an Education Officer, this is the appropriate time to introduce one?

THE PRESIDENT: I think I can say something useful there. The Society has not existed without an Education Officer ever. We have, of course, a very loyal staff here, as you full well know, over whom the duties of the Society are distributed, and they have to carry out its day-to-day work.

What this situation exposes is the fact that the demands which are coming upon us—and what we believe to be good demands in the interests of our Members—are such that our present staff is overworked. They are loyal people; they work hard and put in far more hours than you could possibly imagine as an ordinary Member. It is not until you sit in the Chair in which I am sitting that you find out that the Society is undoubtedly understaffed for the work which is demanded of it. We therefore had in mind to make this position, which would increase the evident educational interests of the Society. It is really a re-distribution of work. I would prefer Members to regard this as an increase of staff rather than to make a special point about it.

May I ask if there are any more points?

DR. KING: May I raise another point, Sir? May I ask the Treasurer what percentage of the membership subscriptions are contributed by the various grades and how he expects this to vary in view of the increases? Does he expect any substantial difference or does he expect it to carry on in the same way?

THE PRESIDENT: I think the questioner is asking what percentage of our total income applies to each grade. I do not know whether you have got the figures there, Mr. Treasurer?

THE HONORARY TREASURER: I have worked out that the increase on Fellows looks like £1,100. The figure for Associate Fellows, of whom there are 4,468, is £8,000. The figure for Associates, of whom there are 2,389, is £4,300. The figure for Graduates, of whom there are 1,215, is £490. The figure for Students, of whom there are 1,405, is £630 and the figure for Companions, of whom there are 195, is £162.

THE PRESIDENT: That does not wholly answer your question but the increases are more or less pro rata.

THE HONORARY TREASURER: It varies with the numbers on that basis. The Associate Fellows, who make up the largest number of people in the Society, should represent the biggest return, that is, about 60 per cent.

MR. N. E. ROWE (*Fellow*): I think, Sir, Dr. King may be exercising his mind about the effect of this rise on the loss of membership.

THE PRESIDENT: Of course, we have discussed that. This is not a thing which any man can predict. However, we are clear, I think, about it in general; in our view, if this involves a loss of membership—and such things usually do—it will not likely have a grave effect on the re-disposition of finances which we have made. We budgeted for a certain loss of membership. It is our belief that when it is all over we will be better off to the degree necessary to do what we have in mind.

I should like to make the point that we do this with full knowledge; we would, on the whole prefer, to finish with a membership whole-heartedly supporting the aims and objects of the Society and the wherewithal necessary to achieve them, rather than a membership which was in any way partial about this. We feel confident we will finish with a membership not greatly decreased, and in so far as it is decreased it will filter upwards in the direction of greater support for the Society.

I do not know whether that again answers your question. We have budgeted for a small loss.

DR. KING: Could I ask where you have anticipated this wastage?

THE PRESIDENT: I do not know for certain but I should think the answer is the Associate Fellows because they are the largest number.

THE HONORARY TREASURER: I expect a few in each grade will disappear.

DR. KING: I would have thought that the largest decrease in membership, not the largest financial loss, would have been in the Graduate grade.

THE HONORARY TREASURER: The total increase would only be £490. I shall be distressed if most of them leave; I certainly hope they will not. They are being asked to pay 8s. a year more. I do not think that is very crucial. It is equal to two packets of cigarettes a year.

THE PRESIDENT: Those who vote for the Resolution at the end of the Meeting—and we hope they will—must have regard to the fact that we will probably get certain losses; we are prepared to face them. We would rather face that than face the consequences of under-running the Society, which we believe will be the greater evil.

MR. WINGFIELD: I would like to speak as an Associate, Sir. From the point of view of the ordinary Member, who does not see much of the Council and its workings, any suggestion for an increase in subscriptions is always unpalatable. However, because we have confidence in the Council and know that they have put forward this proposition, not just to make us feel uncomfortable but, on the contrary, feeling uncomfortable themselves at having to do it, I think we should give the Council our support by passing this Resolution.

THE PRESIDENT: May I ask if there are further questions? Would it be right for me to assume that you are all content and that you have all the information you wish before we put the matter to the vote? I will assume that you are now ready to take the vote. May I ask for the Resolution to be moved?

THE HONORARY TREASURER: I have the honour and privilege of moving the Resolution, much as I deplore having to do it.

MR. N. E. ROWE: I would like to second that, Sir.

THE PRESIDENT: The Resolution is moved by Major Bulman and seconded by Mr. Rowe. I have to draw your attention again to those who are entitled to vote. They are, Founder Members, Fellows, Associate Fellows and Associates. I am empowered to take a vote by a show of hands; a simple majority is sufficient. I have a second casting vote in the event of it having to be used.

The Resolution has been proposed and seconded. May I ask for a show of hands of those in favour?

May I ask for those against?

Would you give us the result?

THE ACCOUNTANT (Mr. Deaton): There are 19 in favour and two against.

THE PRESIDENT: There are 19 in favour and two against. That, I think you will agree, is a simple majority, and therefore I declare the Resolution passed.

That concludes the business of the Meeting. I therefore formally declare the Meeting closed.

(*The Meeting closed at 6.45 p.m.*)

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The Second Lanchester Memorial Lecture

Aeroelasticity—Retrospect and Prospect

by

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The Second Lanchester Memorial Lecture, "Aeroelasticity—Retrospect and Prospect," was given before the Society by Professor A. R. Collar, M.A., D.Sc., F.I.A.S., F.R.Ae.S., on 20th November 1958, at the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1. Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S., presided.

The President referred to Dr. F. W. Lanchester, whose memory the lecture honoured, as one who had greatly influenced the development of aeronautical science and engineering and whose glory expanded the more it was considered. His paper published in 1896 on the circulation theory of lift was 25 or 30 years ahead of others who developed the idea, and his two books, "Aerodynamics" published in 1907 and "Aerodonetics" published in 1908 made fascinating reading now, because in them one found the beginnings of the majority of aeronautical theory as it had developed in the subsequent 30 to 40 years.

The President then introduced the lecturer, Professor A. R. Collar, Sir George White Professor of Aeronautical Engineering at the University of Bristol. The subject of his lecture was aeroelasticity, a subject in which he had acquired an international reputation. Professor Collar was a member of the Council of the Society, the Chairman of the Society's Education Committee and the Chairman of the Bristol Branch of the Society.

On behalf of the Bristol Branch the President presented to Professor Collar a copy of the first edition of Lanchester's "Aerodonetics" a book which they knew he had wanted for a long time.

We look before and after,
And pine for what is not.
—Shelley.

I AM VERY appreciative of the honour that has been accorded me in being invited to deliver the Second Lanchester Memorial Lecture: appreciative, but all too conscious of my own inadequacy. This is especially true, since in the first Lecture[1] we heard a tribute to a very great man from another such: and the prospect of following von Kármán to this lectern is one to deter perhaps all but the most foolhardy. Since von Kármán's address discussed very fully the contributions of Lanchester to aeronautics, little is left for subsequent lecturers on this subject, and I have therefore chosen to speak of a problem which has been my special interest and concern throughout my professional life, namely, aeroelasticity—a field in which, as in so many others, Lanchester was a pioneer. I must first make an apologia and an acknowledgment. I began work on aeroelasticity nearly thirty years ago, under the exceptionally able and inspiring tutelage of Frazer and Duncan and, until 1946, it was my principal field of activity. Academic life, however, nowadays makes many demands on the time of those who embrace it, and since 1946 my part has been largely that of an onlooker, although naturally a very interested onlooker. The conspectus that is attempted here is thus that of—for want of a more appropriate phrase—an "elder statesman": the greyness of my few remaining hairs entitles me to the adjective—*nix capitis probat*—if not to the noun.

Periodically, the Royal Aeronautical Society has published papers on aeroelasticity which have been in the nature of surveys of the problems of the day: for example, Pugsley's lecture of 1937[2], my own paper[3] and lecture[4] of 1946, and Broadbent's lecture of 1956[5]. At this point I would like to express my grateful appreciation to Mr. Broadbent for his help in the planning and writing of this lecture, especially the part dealing with the problems of the past decade: he has an intimate knowledge of this period, and my own slight acquaintance derives largely from contacts with him and his work. My thanks are also due to many other friends and colleagues for help and advice. Since I want to attempt an overall survey of the subject, there can be little of detail in the lecture, and I am only too conscious that many important phases of the subject receive no mention at all; to those who are working in these fields, I offer my apologies.

The solution of aeroelastic problems depends on mathematics, and indeed it is probably fair to claim that the popular use of some branches of mathematics today derives in no small measure from their application to aeroelasticity: a particular example is provided by matrix algebra and analysis. However, I hope to avoid

the use of mathematics in this lecture: in doing so, I am following Lanchester, who wrote in the Preface to the first of his two books, "Aerodynamics" and "Aerodonetics"[6],

> "So far as has been found possible the work has been modelled on non-mathematical lines. . . . Of a mathematical treatise . . . the reader who is only moderately equipped with mathematical knowledge . . . has no great chance of fully appreciating the conclusions."

As is implied by my title, I want first to look back over the history of aeroelasticity from the earliest beginnings to the present day, and then to think for a little about the problems that lie ahead.

RETROSPECT

1. Early History

An excellent short survey of the early history of the subject is given by Bisplinghoff, Ashley and Halfman in their book "Aeroelasticity"[7]. They begin with the very interesting suggestion that wing torsional divergence cost Samuel P. Langley the honour of being the first man to achieve powered flight. It will be recalled that Langley's monoplane was twice unsuccessfully launched from a houseboat on the Potomac river in the Autumn of 1903; Fig. 1 shows the wing collapse that occurred as the second attempt was made. The tests were then abandoned, and on the 17th December of the same year the Wright Brothers first flew under power. Pritchard[8] records how Langley's aircraft, some years after his death, was retested at Hammondsport, N.Y., but only after many alterations had been incorporated; in particular, the system of wing trussing was completely changed. The modified version flew successfully. It may be inferred that, in its original form, Langley's monoplane wing had insufficient torsional stiffness and that aeroelastic distortion was responsible for the failure of his attempts. If this is so, aeroelasticity, although at the time unrecognised and unsuspected, has been plaguing designers since before the beginning of powered flight as we know it.

The effects of aeroelastic distortion seem first to have been recognised by Griffith Brewer; as Fig. 2 shows, he contributed an article to *Flight*[9] in general terms on what we would now describe as wing torsional divergence. But the first quantitative investigation of a particular case of that most feared of all aeroelastic phenomena—flutter—belongs to Lanchester. During a flight in 1916 the Handley Page 0/400 bomber, shown in Fig. 3, suffered a violent tail oscillation, which involved torsion of the fuselage through very large angles, coupled with elevator flapping. It was a box tail, and although the upper and lower elevators were coupled fairly rigidly, the port and starboard sides were independently operated by cable runs from the stick. Thus the connection was very flexible. Lanchester studied this case closely, and recorded his conclusions and recommendations in R. & M. 276[10], Part 1. One of his recommendations was that relative movement between the port and starboard elevators should be prevented by the use of a steel tube of about 2½ in. diameter and 14 gauge; and such a stiff connection soon became a design feature and ultimately a design requirement. Part 2 of R. & M. 276[10] records the mathematical investigation made by Bairstow and Fage at Lanchester's suggestion: it confirmed his view that

> "I also think that the backlash and spring which exists between the right- and left-hand pairs of elevators is a contributory source of trouble: in other words, we may suspect this elastic system of entering into the total dynamic effect."

A similar phenomenon occurred in 1917 on the de Havilland DH.9 and was similarly treated.

In Germany, the effects of wing torsional divergence became troublesome in this period: the Fokker D-8 aeroplane had several accidents due to wing failure. As is evident from Fig. 4, the D-8 was a cantilever monoplane, and it does not look as if the thin wing was very stiff in torsion. During the accident investigation which followed the failures, wing strength tests were made; but these showed the wing design to be adequate from this viewpoint. However, during a test, Fokker observed[11] that as the wing was loaded, it twisted visibly while bending; and he saw that this twist could so redistribute the aerodynamic load as to increase the bending moment to the point of failure. The cure was then obvious. On the whole, wing divergence has not proved a serious problem since that time, although the failure of the Messerschmitt Me.109T during the Second World War (a version with extended span for high altitude work) may well have been due to low effective stiffness as the divergence speed was approached[12].

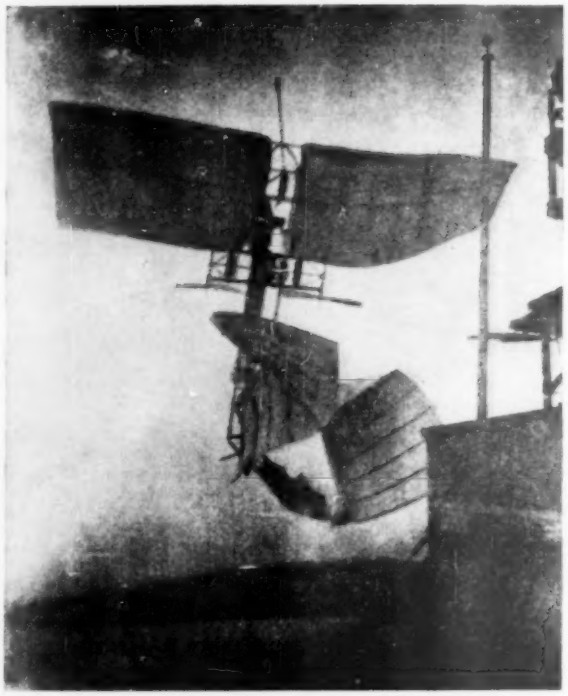

FIGURE 1. Langley's aeroplane collapsing on launching, 8th December 1903.

JANUARY 11, 1913. FLIGHT

THE COLLAPSE OF MONOPLANE WINGS.

By GRIFFITH BREWER.

About a year ago, M. Blériot, with his characteristic courage, reported to the French Government that monoplanes were liable to collapse in the air, not by the breaking of the stays under the wings, but by the breaking of the supports over the wings. Until then the upper stays were regarded as simply performing the office of holding up the wings when the machine was not in use, and it was not until M. Blériot pointed out that these supports could be brought under flying strains, due to pressure being received on the upper surface when a machine is directed downward too suddenly, that makers of monoplanes recognised the necessity of strengthening the upper supports.

In spite of this strengthening, however, accidents in which the wings break downwards continue to occur, and it therefore becomes vitally necessary either to abandon the use of monoplanes altogether, or to look more deeply in order to ascertain the cause of that type of structural collapse.

The suggestion that I wish to put forward is, that a monoplane may be flying in a straight path, and suddenly, without any change in the angle of flight of the machine, the pressure may be caused to leave the lower surface and come on to the upper surface, and thus with a momentum which imparts a sudden strain to the upper wing supports greater than the strain usually carried by the lower stays.

The wings of monoplanes project like arms from the sides of the *fuselage*, and it is therefore obvious that it is easier to twist the outer ends of the wings than it would be to twist the shoulder portions which are attached to the *fuselage*. In fact, the greater the span, the more readily will the wing tips be twisted when subject to twisting strain.

It is more than ten years since the Wright Brothers' experiments at Kitty Hawk, as described by Wilbur Wright in the *Aeronautical Journal* at that time, showed that the centre of pressure before a plane moving through the air at small flying angles, travelled backwards as the angle of incidence decreased and as the speed of the plane increased.

What, therefore, is the effect of change of speed on the wings of a monoplane?

Without changing the path of flight of the machine, the speed of travel may increase, and this causes the centre of pressure to travel backwards thus tending to turn the wings over forwards, owing to the pressure below the front portion decreasing whilst the pressure increases below the rear portion. The effect of this change in the centre of pressure, is a progressive twist from the shoulders of the wings outwards, the left wing twisting like a right-hand corkscrew and the right wing twisting like a left-hand corkscrew. The amount of twist is of course very small and is probably not perceptible to the eye, but with continual changes in the speed of the machine this twisting effect is continually taking place.

This twisting of the wings does not have the effect of changing the pressure from the lower surface to the upper surface until the critical angle is passed, and then the ends of the wings flip over, taking up the slack suddenly.

Let us picture an example of what may take place.

A monoplane is coming down from a height with the engine cut off. Before reaching the ground, the pilot restarts the engine and thus increases his speed of flight, causing the centre of pressure to travel backwards under the wings and tend to turn the machine downwards. The machine, however, aided by the gyroscopic action of the rotary engine, resists being diverted suddenly downwards, and the wings, therefore, bend or twist forward as the pressure decreases under the leading portion and increases under the rear portion. If the change of speed is such as to merely change the position of the centre of pressure without twisting the wings sufficiently to bring the pressure on the upper portions of the tips of the wings, then the use of the elevator corrects the flying angle. If, however, the wings are twisted to such an angle as to bring pressure on the upper portions of the wing tips sufficient to exceed the support below the wings, a quick downward angular movement of the ends of the wings takes place, and the upper stays then receive the strain of the slack being suddenly taken up, in addition to the pressure received from the downward inclination of the ends of the wings. Probably the whip over in the change of direction of the strain does the actual breaking, and the wings then presented to the air at a downward inclination are slammed down by the wind like suddenly released doors.

If this theory is correct, it is not only when starting an engine that this danger occurs. On a windy day, a machine continually rises into whirls, which have the effect of altering the speed of the machine through the air, and also of altering the angle of incidence. The centre of pressure is thus continually moving backwards and forwards beneath the wings, which twist in proportion to the length of their span and the slackness of the stays, and so they are continually approaching towards and retiring from the critical angle, where, if reached, they would whip over to a negative angle.

Change in direction of air gusts, and speed of machine in flight must both have considerable bearing on this question, and when it is remembered that a change of less than 5° in the angle of the wing tips is often sufficient to reverse the direction of pressure on the wings, it will be recognised how close to the safety margin many monoplanes continually fly. The truss systems of the biplane structures make the wings equally strong in both directions, and so this collapse danger is entirely absent.

In all cases a rotary engine would appear to increase the danger, because the wings in twisting find themselves opposed by a mass approaching more than would be the case with an engine having no gyroscopic effect.

I should have liked to have followed up this diagnosis with a curative prescription, but it will perhaps be best to leave my readers to criticise the theory before carrying it any further.

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H.P.L. Exhibits at Ghent.

In the British Section at the Ghent International Exhibition the National Physical Laboratory will have an exhibit illustrating the experimental investigations into the causes of flights carried on at the Laboratory. There will be large scale models of wood channels and also of the spatial tank which presents photographic working tables of the actual curtains and eddies which play about and around the wings and framework of an aeroplane.

33 C 2

FIGURE 2. Mr. Griffith Brewer's article reproduced from *Flight*, 11th January 1913.

Control surface divergence, the effects of movement of centre of pressure due to tip tanks, and the effects of transonic aerodynamics, must, however, be carefully watched[5].

It was during the 1920's that aeroelastic research began on an international scale; flutter was the main problem. In 1922, von Baumhauer and Koning[13] pointed out the importance of inertia coupling in the flutter problem, and proposed the familiar treatment of mass-balancing to cure control surface flutter. Their work was followed up in Germany by Küssner[14]. In Great Britain wing-aileron flutter of the Grebe and Gamecock provided the stimulus for the work of Frazer and Duncan, which culminated, after a series of interim reports, in the publication in 1928 of R. & M. 1155, "The Flutter of Aeroplane Wings"[15], known to aeroelasticians as the "Flutter Bible." This is a remarkable work: even after thirty years it is difficult to find any phase of the flutter problem which is not recognised and given some treatment in it. Methods of analysis have changed; the problems are different and there are more powerful tools to treat them; but the fundamentals of today's work may still be found in R. & M. 1155. Many simplified accounts of the subject have since appeared, which are more readable and topical—Duncan's "Fundamentals of Flutter"[16] and the relevant part of Broadbent's "Elementary Theory of Aeroelasticity"[17] for example; but both refer the reader to R. & M. 1155 for more extended accounts of the subject.

2. The Emergence of New Problems

Around 1930, the development of stressed skin construction finally brought about the demise of the biplane and the triumphant resurgence of the monoplane. But there came with the monoplane not only higher performance, but also a crop of aeroelastic troubles. The stiffness derived from interplane struts and bracing wires was gone and intrinsic stiffness was not yet adequate. The next decade was therefore a time of great development in the aeroelastic field.

The flutter problem continued, cases of wing-aileron and tail flutter[18] being reported and studied: the research into the accidents to the Puss Moth[19] is an example. Loss and reversal of aileron control was a new problem, but one which assumed increasing importance with the years; it was elucidated by the work of Roxbee Cox and Pugsley[20], and was one of the important factors leading to the development of stiffness criteria[21]. While this work was proceeding, the first serious cases of buffeting appeared, and one accident at least, in which structural failure resulted from buffeting[22, 23], was closely investigated.

Yet another problem was provided by the upfloat of ailerons—particularly Frise ailerons—against circuit stiffness. The excellent aerodynamic characteristics of the Frise aileron derive from a feature which also gives a very non-linear hinge moment. So long as stretch of the circuit is small, a pair can be nicely balanced; but if upfloat is serious, overbalance, snatch and divergence can result[24]. During this decade, the search for higher propeller efficiencies led to thinner blades, and to

FIGURE 3. The Handley Page 0/400.

FIGURE 4. The Fokker D-8.

flutter[25]; similarly, the first aerodynamic servo tabs appeared and were also at once bedevilled by flutter[26]. Finally, to put a period to what (from the designer's viewpoint) is a dismal catalogue of troubles—but which could nevertheless be extended—at the end of the decade, when in view of the Second World War aeronautical development was at its height, elastic distortion began to affect the rigid body stability of aircraft as a whole: previously, aeroelastic effects had been largely confined to components. Early researches on the variation of stability due to distortion[27, 28, 29] were reported during this period.

While these problems were appearing and intensive studies of their nature were proceeding, it was natural that those concerned should cry out for data on the aerodynamic loads involved. Experimental work, although difficult and slow, proceeded steadily; in parallel, theoretical predictions of the magnitudes of the derivatives involved, and their dependence on frequency, began to appear[30, 31, 32, 33]. I shall return later to the important subject of aerodynamic derivatives.

Finally, perhaps I may, with proper humility, mention the appearance in 1938 of a volume entitled "Elementary Matrices" by Frazer, Duncan and Collar[34]. This work derived almost entirely from the authors' interest in, and use of, matrix analysis as a practical mathematical tool for the treatment of aeroelastic problems; its appearance in book form was due to the view of the Aeronautical Research Committee that some of the authors' papers were too recondite for publication in the usual aeronautical literature. The Committee therefore recommended that the researches should be welded together to form the substance of a book. Twenty years later, matrix methods are standard in all aeroelastic and vibration theory.

3. The Integrated Approach

The rapid strides in aircraft performance that were engendered by the Second World War brought a spate of aeroelastic troubles of the kind already detailed. These troubles, of course, came directly to the attention of those concerned with design requirements. At first the troubles were mostly unrelated, although the connections between certain phenomena had long been known. Frazer and Duncan's work[15] had shown divergence to be a part of the flutter problem, implicit in the same piece of analysis; the early workers on aileron reversal[20, 35] had shown its relation to divergence. But there is no obvious connection between, say, mechanical vibration and longitudinal stability. However, it was well known that measures aimed at safety in one phase of flight could mean danger in another phase. For example, a *g*-restrictor is an obvious safety device. The simplest form of *g*-restrictor is a mass attached near the trailing edge of an elevator; but while this may prevent the pilot from applying excessive normal acceleration, it is also one of the surest methods of promoting a destructive flutter.

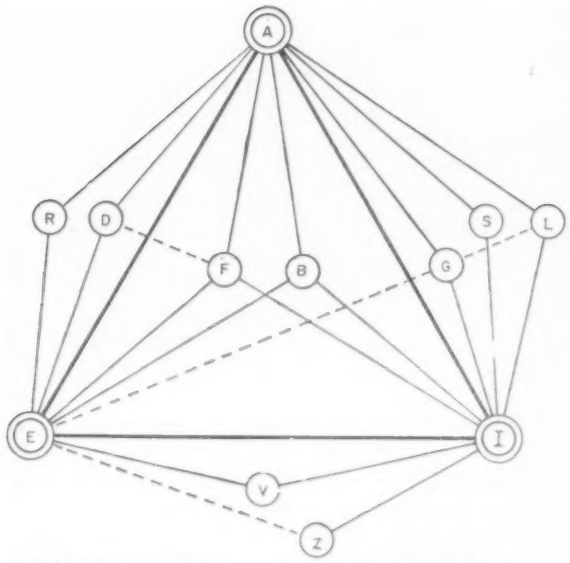
Clearly, then, elevator flutter and aircraft manoeuvrability are related phenomena. There is a more obvious relation between mechanical vibration and flutter, and so we find links between such apparently unrelated things as vibration and aircraft stability. To those concerned at the time with requirements for the prevention of aeroelastic troubles, other links were apparent. These considerations led to the evident conclusion that each phenomenon in the category of aeroelastic problems was, in fact, only one phase of a more general problem, the dynamics of a deformable aircraft. This concept prompted the writing in 1946 of "The Expanding Domain of Aeroelasticity"[3] which drew attention to the merging of the problems into each other and into other problems outside the aeroelastic field. I shall venture here, with some diffidence, to reproduce in Fig. 5 a diagram from that paper, since I have been told it has been helpful to aeroelasticians in the past few years*. There are three principal types of force involved in aircraft dynamics: aerodynamic, elastic, and inertial. If we denote them by A, E, I and arrange them in a "triangle of forces" we can relate our dynamical phenomena to them as indicated in the diagram, and see at once the connections between the phenomena.

From these considerations, an obvious question emerged. Could we not solve all our aeroelastic problems in one fell swoop by treating the dynamics of a deformable aircraft? In theory this was certainly possible, but the complexity of the problem ruled it out in practice. There was, however, a ray of hope; automatic calculating machines and electronic devices were being studied and offered the possibility of enormous advances on the capabilities of the machines of the day. It seemed just possible that such machines could tackle the very complex general problem. If a quotation may be permitted—

> ". . . we obtain a set of simultaneous differential equations, probably in twenty to thirty degrees of freedom which describe completely the motion of the aircraft. . . . From a practical viewpoint, of course, the labour of dealing with such a set of equations is prohibitive at present. But in the last few years considerable strides have been made in dealing with large numbers of simultaneous equations by electrical, mechanical, and electro-mechanical machines, while the growing use of matrix algebra makes the formulation of the problem, as well as its solution, much easier. It is thus not outside the bounds of possibility that within a period of years we may have available computational aids of such power that the solution of equations of the kind we are considering may be a routine process."

Computational engineers have, in fact, now turned this pipe-dream into a reality; but the rapid advances that have been made have been enormously helped by another factor. Aircraft designers recognised that the growing importance of aeroelasticity merited the formation in their own organisations of sections specialising in the subject; and to these sections they recruited mathematicians, physicists, and electronic engineers, in addition to aerodynamicists and specialists in structures. These groups have made far-reaching contributions to the study of a subject which, in Great

*See, for example, Refs. 7, 56 and 64.



A Aerodynamic forces.
E Elastic forces.
I Inertia forces.
F Flutter
B Buffeting
S Stability and Control
D Divergence
R Reversal of control
G Gusts
L Loading problems
V Mechanical vibration
Z Impacts

FIGURE 5. Triangle of forces.

Britain at least, had long been the almost exclusive preserve of two Government Departments. This development is to be heartily welcomed. Quite apart from the immediate purpose of studying and anticipating aeroelastic problems from the design stage onwards, the formation of such teams has implied a closer integration of effort inside the firms. The aeroelastician is concerned with both the aerodynamic and structural properties of an aircraft; in his problem, each reacts back on the other in a closed loop—in some cases the loop is a vicious circle. His presence in the aircraft organisation therefore provides a powerful additional link between the aerodynamics and structures groups. It means, moreover, another step towards the position foreshadowed over twenty years ago by Roxbee Cox[36], who said in effect that ultimately the problems of stiffness and strength must be regarded as the problem of designing a *stable* structure for the applied loads, and solved by a co-ordinated effort.

4. Some Important Recent Developments

It is a difficult task to select from the developments of the past few years those of greatest significance, and any selection is bound to be in some degree arbitrary. However, the importance of some of the developments to be described is undeniable.

4.1. FLUTTER SIMULATORS AND COMPUTATIONAL AIDS

Mention has already been made of the fact that the work of computational engineers has provided the tools for a solution of the integrated problem, the dynamics of a deformable aircraft. The existence of electrical analogues of mechanical systems had been known for many years, and had been put to some practical use. The application of this analogy to the flutter problem presents many difficulties, however, and many interesting techniques had to be developed for it. For example, the dependence of the aerodynamic coefficients on a single parameter, the flight speed, implies the multiplication of coefficients in various ways and their ganging in related groups.

In Great Britain, the design of a flutter simulator was first undertaken by Smith[37] and his collaborators at the R.A.E. They first produced a simulator in two degrees of freedom: a small machine, but with the necessary techniques developed, so that the building of larger machines, although complicated and costly, did not involve much further development. From the two degrees of freedom, the R.A.E. proceeded to a machine with six degrees of freedom, shown in Fig. 6, and this simulator[38] has been of immense help in the elucidation of many problems of flutter and stability. It is still an arduous process to evaluate the coefficients in the equations of motion, but once this is done, the solution is a matter of minutes, where previously months were required. Moreover, variations in the equations (such as the effects of changing products of inertia, or finding how important some sketchy data are) can be dealt with very rapidly and simply. If anything, the difficulty is no longer in the great time required to perform a flutter investigation, but in the mental indigestion that can result from too many investigations in too short a time.

The building of the R.A.E. simulator was followed rapidly by individual designs, based on the same general principles, but often employing different techniques and components, at a number of aircraft firms: Avro, Bristol, Saunders-Roe, Short and Vickers were early in the field. The Vickers simulator has nine degrees of freedom and is capable of incorporating non-linearities into various phases of the problem. It is believed that this machine can deal not only with flutter and stability, but also with stressing problems: it shows that an approach to the integrated problem is now a practical possibility[39].

In parallel with the development of simulators, there has been great progress in the use of digital computers. So far as I am aware, the first digital computers to be applied to aeronautical problems in Great Britain were the Hollerith machines installed at the R.A.E.; but it was soon apparent that more specialised machines were needed, and in the development of these much pioneer work was done at the N.P.L. and in America. These computers are capable of solution of sets of equations in large numbers to very high accuracy in very short times. Their work is complementary to that of the simulator; often they can be used for parts of the preliminary formulation of the equations of motion, such as the determination of normal modes of vibration, as well as for the complete solution.

4.2. GROUND RESONANCE TESTS AND NORMAL MODES

Resonance tests on aircraft have been conducted for many years, but the interpretation of the results

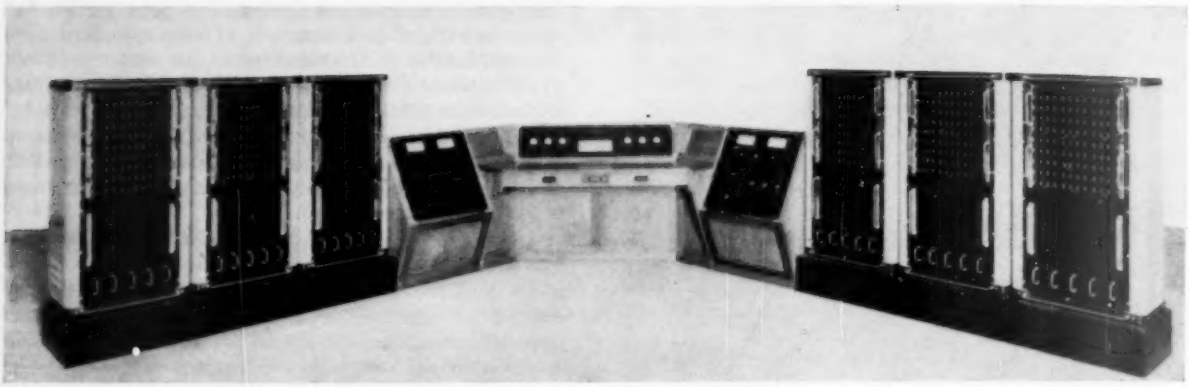


FIGURE 6. R.A.E. Simulator.

was, in the early days, much more of an art than a science. The results were used more for qualitative appreciation of such things as the efficacy of a balance mass than for quantitative use in an analytical flutter investigation. However, when it became increasingly apparent that flutter usually involved far more degrees of freedom than the two or three employed in a calculation, Duncan[40] suggested that since all parts of an aircraft participate in a normal mode, the use of normal modes might well imply economy of effort. While there is still some doubt about this point (and it is a less important consideration than formerly), it has proved well worthwhile to concentrate on normal modes, since their relatively light coupling implies that the equations to be solved are well conditioned and suited to solution by the computational aids described earlier. Moreover, the normal modes appear in a regular spectrum of frequencies; and since it is usually possible to make a reasonable forecast of the flutter frequency, one can choose a range of the spectrum straddling this frequency, and be tolerably certain that the essential modes will be included. Other advantages of normal modes have been discussed by Broadbent[37].

Ground resonance tests have thus increased in importance, and have, in fact, become mandatory. Refinements of methods of test have followed in due order. Electronic methods of excitation and detection have become increasingly used and provide increasingly accurate results. There is, however, an important difficulty still awaiting a completely satisfactory solution. In the absence of all damping, the structure would respond at its natural frequencies in its natural modes, with every part of the structure moving in phase (or antiphase); nodal lines could be determined with accuracy. But, in fact, structural and other damping affects this simple picture, and affects it especially as the higher frequencies are approached; amplitudes at points remote from the exciter are much smaller than they should be, and many parts of the structure move in quadrature with, or at least with major phase changes from, the master station. No nodal lines are apparent; only regions of minimum amplitude. What then is the normal mode? Further, with this somewhat amorphous response, can it be certain that an important mode has not been missed in a test? If the exciter is on, or near, a natural nodal line, there may be negligible response.

Devices aimed at the solution of these difficulties are being developed. Multi-point excitation is a possible solution, with the exciters accurately phased to ensure absence of response in quadrature: the absorption of energy throughout the structure is matched as far as possible by energy input at a spread of stations. Methods of support of the aircraft are being improved to give minimum constraint; analytical devices to interpret the response and to deduce the normal mode are also under consideration (for example, the analysis of Kennedy and Pancu[41], and the experimental techniques it has stimulated). It is a problem of world-wide interest.

4.3. ELASTIC MODELS

Aeronautical design has always relied heavily on model work, and models have played a big part in aeroelastic investigations from very early days. Usually, they were employed to determine the relevant aerodynamical derivatives; less often for flutter experiment. The latter is a difficult matter; for test in a conventional low-speed wind tunnel a simple model is usually much too stiff, so that reduction in the natural elasticity is often required and has to be made artificially. This, in turn, makes the proper disposition of mass difficult and, as a result, the normal modes of the model and aircraft are liable to be considerably at variance.

However, the immense saving in effort, time, and money offered by model work has increased its importance as the years have passed Three phases deserve mention.

The development of materials such as Xylonite has meant that it is possible to construct scale models[42] of an aircraft structure, even to small detail, so that the elastic and inertia properties of the structure are accurately represented; while the elastic modulus is so low that tunnel investigations at reasonable speeds are possible. These methods can also be used for the determination of normal modes to be employed in preliminary flutter calculations, although they suffer from the defects associated with interval damping.

Where compressibility effects are important other

types of model are required; they must be capable of withstanding the loads experienced in a high speed tunnel which reproduces the Mach number of flight accurately. The dynamic pressure may be different, but if so, the density of the model must be adjusted to give the appropriate density ratio. The construction of such models has become so specialised that in America it is largely undertaken by one firm, Dynamic Models Inc., for the rest of the industry; and it may prove economic to follow a similar course in Great Britain and elsewhere.

The use of such models requires high-speed wind tunnels, and these are scarce and are usually heavily in demand for other purposes. Effort has therefore been devoted to the design and construction of models carried by rocket vehicles[43] to high speeds (and to a much less extent, of models falling freely from great heights). The flight characteristics of the models are measured and the results transmitted by telemetry to the ground. Unfortunately, of course, this form of experiment is very costly and may often yield negative results. Nevertheless, very useful information has been obtained in this way.

4.4. FLIGHT FLUTTER TESTING

When the speed of an aircraft is increased towards a critical condition, the overall damping becomes less; accordingly, there is a greater response to an imposed vibration or other excitation. Use can be made of this fact[44] to study the properties of the aircraft in the range below a critical speed, and to make comparisons with calculations; steps to avoid trouble can then be taken with confidence. These considerations were early apparent[45, 46]; however, Frazer and Jones[47] showed that such an experiment could be misleading, while a report of trouble in German flight experiments suggested that it might be dangerous. It is only recently that the development of more sensitive and accurate pickups and devices for analysing response, and of more reliable methods of excitation (including the simple "bonker") has enabled the tests to be undertaken usefully and without undue risk. This is a most important technique, of course, since it involves a test of the actual aeroplane in the actual flight condition: the ultimate test, in fact. Calculations, based on resonance test data and on estimated aerodynamic loads, are made of the response of the aircraft to an imposed disturbance (either a single frequency oscillation, or more usually a disturbance containing a range of the frequency spectrum) over a range of increasing flight speeds. Comparisons are made with actual response in flight, beginning with low speeds; where differences occur, they indicate new calculations refining (for example) the aerodynamic loads. The tests are continued to increasing speeds, modifications being made if the tests and calculations indicate the necessity for so doing.

4.5. OTHER DEVELOPMENTS

What has been said so far relates entirely to the general problem of avoidance of flutter, which is by general consent the most difficult and dangerous of the aeroelastic phenomena. But there are other phenomena, and other aspects of vibration, which have demanded attention in recent years and which deserve at least a brief mention.

Loss and reversal of aileron control, although well understood, still awaits a new solution; meanwhile, it has become the dominating factor in wing design. A recent survey covering about 30 aircraft shows that over half have wing designs which were dictated by aileron reversal considerations; as against this, strength was the dominating factor in less than a quarter of the types, and they were mostly aircraft with unswept wings, not intended for very high speed work. It would seem that this state of affairs must persist so long as the conventional aileron is used.

Power-operated controls have posed a number of problems. Theoretically, they offer irreversibility, long recognised as a powerful means of prevention of flutter and vibration; in practice, they have elasticity, often variable (for instance, if the fluid becomes aerated), damping, and sometimes an inherent instability which can produce and maintain unpleasant vibration or worse. The study of these problems has been helped greatly by the use of impedance testing, and by researches into analytical devices, such as Duncan's work on mechanical admittances (receptances)[48].

The great progress in power plant design, and in particular the thrusts available from rockets, imply much higher accelerations than those to which we have been accustomed. Now, in studying the stability of an aircraft or its components, we conventionally regard the speed at any instant as fixed. The coefficients in the equations of motion, being functions of speed, are thus constants; and the solution and properties of linear second-order differential equations with constant coefficients are well known and understood. If, however, the speed must be regarded as varying with time, the aerodynamic coefficients become variables also, and a much more complicated problem demands solution. A small beginning has been made here[49]; it indicates that the effect of acceleration depends on a dimensionless number (allied to the Froude number) in which—perhaps fortunately—high acceleration is to a large extent offset by high speed. At the same time, it is clear that a system which is stable at constant speed can become unstable if sufficient acceleration (or deceleration) is imposed.

The increasing use of T-tails has posed a number of problems. The strong downwash field behind a swept wing of small aspect ratio has tended to demand an all-moving tail set at the top extremity of a relatively slender fin. From the aeroelastic viewpoint this requires careful consideration: a mass of high inertia set at the top of a flexible structure, with an operating mechanism of robustness limited by the demands of aerodynamic cleanness—here are all the ingredients for distortion and vibration of relatively low frequency. Moreover, operating loads may, for example, cause changes in dihedral angle, and these can mean serious changes in inertia coupling, and the development of instability.

Finally, gusts, high speed (shock wave) buffeting, "buzz" of controls, and tabs have all provided problems in recent years.

PROSPECT

5. Some Speculations

In the last section it was evident that during the past few years aeroelastic phenomena and troubles have lessened neither in number nor in importance; and with that review I conclude my retrospect. From contemplation of the solid ground of factual experience of the past, I now turn to the task of attempting to pick a path through the quicksand of speculation on the future—a journey made more hazardous by the likelihood that I shall try to ride certain personal hobbyhorses.

May I begin by expressing the opinion that aeroelasticity will continue to play no less an important part in the aeronautics of the future than it has throughout the past half century; but—and this is the important point—I think incidents and accidents due to aeroelasticity will decrease. It is still a difficult and somewhat mysterious subject, but the great increase in the number of those familiar with it and actively concerned with it, particularly in the Industry, means that there is an increasingly good chance that the problems it poses will be met. The happenings of past years, frightening then because they were not foreseen and not understood, are seen now, not as examples of "the total depravity of things inanimate," but as occurrences of simple mechanical origin. Indeed, it may well be that we may see the successful deliberate use of aeroelastic properties to improve flight characteristics; Hill proposed the aero-isoclinic wing with this object. This is no new idea—the Wright Brothers used warping wings for lateral control—but in recent years the unknown hazards of any such attempt have ruled against it.

In future work on aeroelasticity, whether it be in enlisting its aid or avoiding its unpleasant phenomena, there will, of course, continue to be some troubles and difficulties; although much ground has been covered, there are still many areas of which the understanding is less than it should be. Inevitably, too, the future will bring new designs which will present new problems. But I believe we now have a much better chance of successful anticipation of trouble than was the case in the past. Aeroelastic considerations must be kept in the forefront of design—it has been noted that they are already the dominating factor in wing design—and aeroelastic teams must be kept at full strength. With the steadily increasing power of computation now available, it should then be possible, not just to meet the troubles half-way and to compound some settlement with them, but to go the whole way to ensure they do not obtrude at all.

I have mentioned some areas which are imperfectly understood; I would like to examine some of the more important in greater detail.

6. Correlation of Calculation and Test

It has been remarked earlier that much importance is at present attaching to the results of flutter and stability calculations, to the accurate interpretation of ground resonance tests, and to the use of flight flutter tests. It is, however, unfortunately true that at present these approaches give results which are often considerably at variance with each other, and one of the urgent problems of the near future is to secure better correlation between them.

In broad and somewhat idealised terms, when a new design is crystallised, the firm's aeroelastic team determine from the drawing board the distribution of mass and elasticity, to define the mechanical properties of the aircraft. Preliminary flutter calculations are then made, possibly using arbitrary modes in the first instance, to see if there is an immediately obvious need for design changes. Next, calculations are made of the normal modes and frequencies which will appear in a resonance test; and then, using an appropriate choice of normal modes, flutter calculations are made, including (throughout the speed range) predicted responses to the disturbances which will be applied in the flight flutter test. The building of the aircraft proceeds meanwhile and in due course an aircraft is made available for resonance tests. All too often, the results of the tests show considerable variation from the earlier calculated results: nodal lines in particular can look markedly different in the calculated and experimental pictures. At once the question arises: since the mechanical properties of the actual structure show pronounced variations from calculation, how much reliance can be placed on the calculations of response in flight? Yet another source of possible error is involved here, since the aerodynamic forces used have not been measured.

The logical step is to repeat the response calculations using the measured modes, of course; but this is a lengthy process and there will be a very natural desire to get the aircraft airborne as soon as the resonance tests are complete. The only real solution is to improve methods of calculation of the mechanical properties (in particular, of stiffness distribution) and to improve the resonance test techniques in the manner discussed earlier, so that good correlation is obtained.

When this goal is attained, there remains the question of correlation with flight test results. The choice of a limited number of degrees of freedom (whether normal modes or not) implies an unknown degree of inaccuracy, in addition to that resulting from the possible errors in the assumed aerodynamic forces. In a flutter occurrence, the modes participating must do so at the single flutter frequency; they are therefore no longer at their own natural frequencies, and variations in modal shape must be expected. Probably one of the most helpful things in improving correlation here will be the building up of a body of results, to obtain the experience necessary to guide the workers in the choice of co-ordinates.

I would like to mention here a form of test which may help to bridge the gap between flutter calculations, based on normal modes, and flight flutter tests. In the University of Bristol, work on a small scale has been going on for some two years on the development of a system which attempts to simulate on the ground the air forces which would occur in flutter. In practice, this would mean taking the actual aircraft, and by means

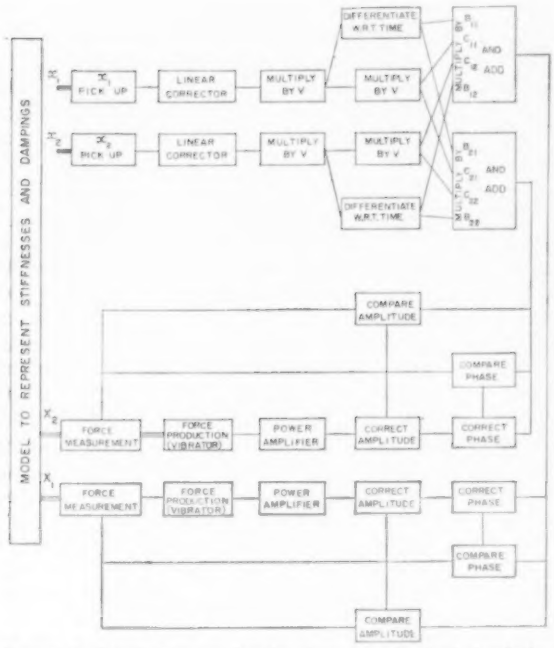


FIGURE 7. Block diagram for the electro-mechanical simulation of air forces.

of suitable pickups obtaining signals of any distortion; these signals are fed to a device which calculates the air forces at any forward speed corresponding to the signalled distortion (after suitable coupling and addition) and feeds the result through an appropriate amplifier to a forcing mechanism which applies the equivalent of the aerodynamic loads to the structure. As yet, the work done has related only to a simple pilot system, shown in Figs. 7 and 8; it has functioned very satisfactorily. This proposal has both advantages and disadvantages. It could replace the resonance test, so that no question of finding and applying normal modes would be involved; if the aircraft is liable to flutter in the air, then it will flutter on the ground. It should therefore be possible to conduct a "flight" flutter test on the ground, not only at speeds below the critical, but beyond also, without risk to the aircraft and crew, and without the difficulty and expense of flight. As against these desiderata, the loads applied must be based on calculated aerodynamics, and they can only be applied at a limited number of points. Moreover, the apparatus, if on any large scale, is complicated and costly. Nevertheless, the idea offers another weapon in the armoury of the aeroelastician; and it is of interest to note that since work began on it in Great Britain, we have learned that similar ideas are being examined in Germany and America.

I want to say a word or two later about the use of models in surveys of the flutter problem; clearly they offer an additional source of information and a chance of resolving conflicting evidence from other sources. To conclude this discussion, it is of interest to summarise the possible approaches to the solution of the flutter problem on a new aircraft as follows: —

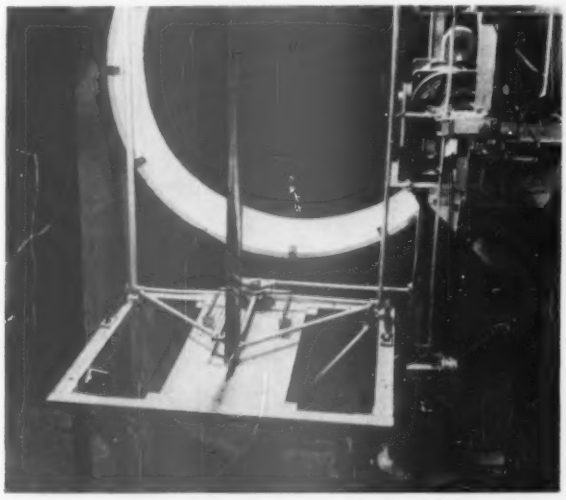


FIGURE 8. Flutter apparatus for the electro-mechanical simulation of air forces.

(*a*) Calculation of structural, inertial, and aerodynamic properties of the design.
(*b*) Preliminary flutter calculations; also predictions of the normal modes.
(*c*) More extended flutter calculations, and response calculations, based on the predicted normal modes.
(*d*) Construction of a model or models, and determination of the normal modes on this scale.
(*e*) Wind tunnel tests of the model, for checking of aerodynamic derivatives and for flutter measurement.
(*f*) Ground resonance tests of the actual aircraft.
(*g*) Ground flutter tests.
(*h*) Flight flutter tests.

Each of these approaches has its part to play, and can contribute valuable information; but we have a good deal of research and development to face to ensure good correlation between the results, which alone will ensure real confidence in the immunity of the aircraft from aeroelastic trouble.*

7. Models and Dimensional Analysis

Much of what I want to say under this heading is speculative in the extreme, and would perhaps be out of place in a lecture of this kind were it not that Lanchester himself regarded dimensional theory[80] as one of the major analytical tools of the engineering profession.

First a word about models: although emphasis is increasingly placed on the ultimate test of the flight of the aircraft, I do not think model work will lessen in

*At this point a short film was shown, demonstrating the electro-mechanical flutter simulation apparatus shown in Fig. 8. The apparatus was developed in the Department of Aeronautical Engineering, University of Bristol, by Mr. A. S. Palmer under the supervision of Mr. T. V. Lawson. The film was produced by Dr. J. Black and the photography and editing were the work of Mr. G. W. Brandt of the University's Department of Drama.

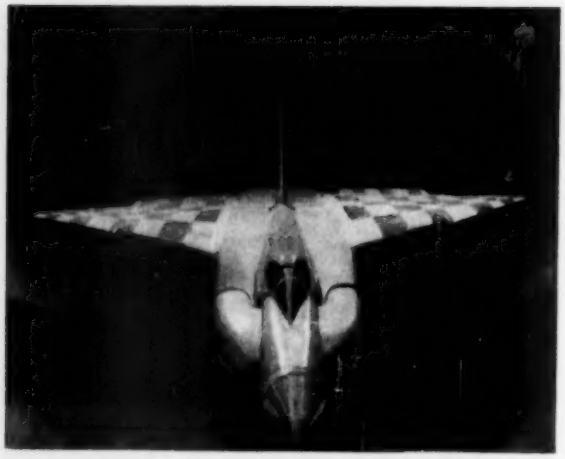


FIGURE 9. The Avro Arrow Flutter Model.

importance. The experimental determination of aerodynamic load, and especially its dependence on compressibility effects, is a matter as vital to the aeroelastician as to the other members of design teams. Elastic models are difficult and expensive to make, but they offer the possibility of far more extended experiment than the full-scale aircraft, and this implies that model work is one of the best avenues to a fuller understanding of the aeroelastic problems of the aircraft, and therefore to the most economical and satisfactory solution of those problems. Fig. 9 shows the flutter model of the Avro Arrow, the design of which was described by Floyd in the Society's Fourteenth British Commonwealth Lecture[51].

It seems clear that there must be considerable research and development in the model-making field: it may well become a small industry in its own right. Mention has been made earlier of the use of Xylonite and similar materials; this technique owed its development in large part to the fact that the material is readily cemented. It is now becoming possible to make models to representative scantlings in the correct materials, using very fine gauges and a modern bonding process: even welding is now possible for sheet thicknesses down to 0·005 in. At the R.A.E. another exceedingly interesting development is being explored by Molyneux and Guyett: that of construction of models by electroforming. This involves the making of a mould, spraying with silver, and then depositing the metal by electroplating; ingenious devices are used to control skin thickness. Fig. 10 shows a model formed in this way. This process offers the possibility of building models having varying skin thickness, a technique that may become very important for obvious reasons. Developments involving a "lost metal" process are also possible, which may mean that a plated skin can be built on to, and made integral with, an internal structure. Soon it should be possible to make truly representative models, and this will greatly help in providing solutions to aeroelastic problems at an appropriately early stage in design.

Models, of course, are used for the measurement of aerodynamic derivative coefficients, and I now want to offer some speculative thoughts on the definition of such coefficients. If the flow pattern round an aerofoil does not change with speed, a force is proportional to the product $\rho V^2 S$ (in the usual notation) and we obtain a coefficient by dividing the force by this product. In fact, of course, the flow pattern does change, with such parameters as incidence, Reynolds number, Mach number and, if the aerofoil oscillates, with frequency parameter. In flutter work it is often convenient to assume the variation of force with incidence to be linear and to divide the force coefficient by the incidence, or a dimensionless form of rate of change of incidence, to give flutter derivatives. Some twenty years ago, Great Britain decided to adopt the limited range of coefficients based on $\frac{1}{2}\rho V^2$ which were common elsewhere: a retrograde step, since there is no virtue in the numeric $\frac{1}{2}$ and it cannot logically be introduced into, for example, propeller and rotor coefficients, or velocity derivatives; moreover, it has not been introduced into flutter coefficients. The present situation is, to say the least, untidy. Nowadays, the dependence of coefficients on Mach number is becoming exceedingly important, and we have the additional untidiness of coefficients which, already dependent on V, are also functions of V in the form $M = V/a$. It has, for example, become necessary for a Panel which recently considered certain definitions[52] to define two different quantities, kinetic pressure and dynamic pressure, to take some account of Mach number effects.

There is an opportunity here for a clearing up: instead of using ρV^2 or $\frac{1}{2}\rho V^2$ we can use pM^2 where p is the ambient pressure[4], and the dependence on Mach number can then be absorbed into a single function. This suggestion has also been made in America[53]. Is such a change worthwhile? Viewed in isolation, perhaps not; but shall we be faced with other changes if, for example, the European common market comes about: will it be expedient for aeronautical engineers, like our electrical brethren, to adopt the MKS system of units? If we do make one change, we might well begin *de novo* and incorporate the other.

These are interesting, if idle speculations. I suspect that what is entrenched will continue to hold the field, even at the expense of logic. Such was Lanchester's experience; it will be recalled that Lanchester, in his book L.M.T.[50], annihilates the slug-foot-second system of units (even in three distinct guises) on logical grounds. But while there is no question that his logic was faultless, the slug-foot-second system has continued to flourish in aeronautics, partly because it was entrenched, but mainly because the pound as a unit of force is convenient if one has to lift an aircraft weighing so many pounds: and this despite the fact that, as Lanchester shows, the precise definition of the pound force is an illogical and arbitrary business.

8. The Part Played by Damping

It has always been a matter of some surprise to me that the part played by damping in the promotion of flutter is so imperfectly understood, and I think that

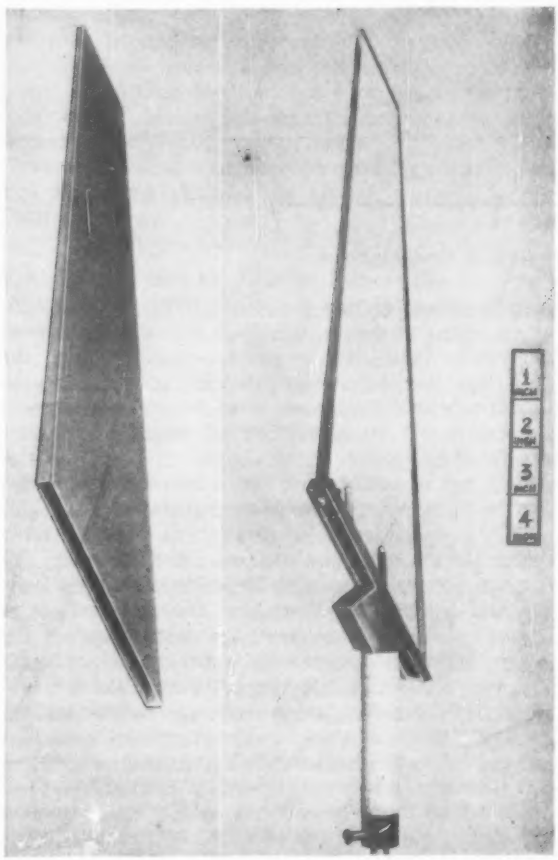


FIGURE 10. Nickel plate torsion box and former.

before long a major effort to elucidate this matter will be required.

Since damping absorbs energy, it was thought when flutter first occurred that artificial damping might be used for its prevention. However, attempts in this direction, aimed especially at curing control surface flutter, were failures. Calculation showed that, in very many cases, the introduction of small amounts of artificial damping lowered, rather than raised, the critical speed for flutter; if the damping were progressively increased, flutter might ultimately be eliminated, but the degree of damping required for this was quite impractical, at least for manual control. Power operation, while it could no doubt overcome the damping resistance, has its own characteristics of damping and irreversibility which cast doubt on the desirability of a mixed system.

Despite this difficulty, aeroelasticians have frequently returned to this topic. Proposals have been made for the use of tuned dampers, which would have a high energy absorption at the flutter frequency only. The use of quasi-irreversible controls has also been suggested; here movement initiated by the pilot frees the system from the heavy damping opposing movement beginning in the control. Other proposals of the same kind are on record, and it is natural that they should appear: it certainly ought to be possible to use damping to improve flutter characteristics. Experience seems to show, however, that until the mechanism by which damping affects flutter is better understood, attempts to use it are more likely to worsen the characteristics than to improve them.

It is of interest to enquire, in general terms, how the paradoxical result comes about that the introduction of artificial damping, which absorbs energy, should in practice bring about a gain in energy in the fluttering system. The answer must lie in its effect on the relative amplitudes and phases of the motions participating: it is readily demonstrated that the rate of energy absorption from the air depends on these quantities. It is well known that an undamped mechanical system subjected to a forced vibration responds in phase (or antiphase); but if damping is introduced, the relative amplitude changes and phase differences develop. Clearly, when the introduction of damping worsens the flutter characteristics, it is so changing phases and amplitudes that a greater influx of energy occurs than the damping absorbs.

This simple picture is complicated by the fact that, even in two degrees of freedom only, there are four dampings, two direct and two cross. Moreover, instability with phase differences can result from the development of unsymmetrical cross-stiffnesses, even in the absence of damping. As a result, an attempt at analytical examination of even the simplest case produces a complicated picture with six coefficients heavily involved. R. & M.1155[15] gave some attention to this matter and, in particular, studied the energy balance throughout a cycle of oscillation: this approach deserves further study, along the lines suggested in "The Fundamentals of Flutter"[16].

There have been a few contributions to clearer understanding in recent years. A paper by Templeton[64] showed how phase angles can affect instability; more recently, an investigation by Broadbent and Williams[65] has appeared, in which vector diagrams are used to demonstrate the phase and amplitude changes resulting from the introduction of damping. But we still lack a simple general rule which says "if damping is introduced in this way, an improvement will result."

A particular case has been studied in the University of Bristol which shows that improvement can result; it is diagrammatically shown in Fig. 11. The system considered is that of a pure aerodynamic servo (or spring tab), and the two degrees of freedom are control surface and tab rotation. Such a system is well known to be prone to flutter; but if the tab is geared to the control, it must move in phase or antiphase, so that a degree of freedom is effectively removed and flutter is impossible. The damping unit shown was devised so that, when for rapid movement it becomes effectively locked, the tab becomes geared to the control; however, for slow movement or stationary conditions, the unit offers little or no constraint, so that the pilot's effort is minimised. Thus the unit is aimed at an alteration of phase angle in the direction of safety; and experiments with it have proved successful. However, it cannot yet be claimed that this is a uniformly successful device; there remain questions if the follow-up ratio is changed.

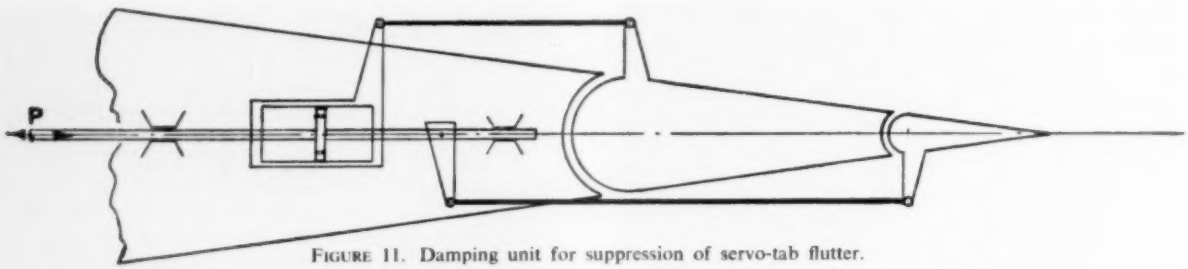


FIGURE 11. Damping unit for suppression of servo-tab flutter.

It is of interest to remark, in this Lecture, that this device has much in common with Lanchester's friction damper for torsional vibration. It will be recalled that this was a flywheel bolted to a flange on the crankshaft concerned; however, if the bolts were loose, no friction and no damping resulted, while if the bolts were tight, the flywheel was locked and no relative movement—and again no damping—occurred. The appropriate condition was an intermediate one, permitting relative movement but against a frictional load. In the case of the flutter damper, the damping must be intermediate also: low damping has no effect, while high damping removes a degree of freedom and impairs the aerodynamic value of the system.

To sum up, the paradox of damping remains for solution. There are some glimmerings of light, but much needs to be done for a full understanding of its effects.

9. Problems of Very High Speed

The first excursions towards sonic speeds were made possible by postponing the more serious compressibility effects by the use of sweepback. This device entailed a multiplicity of aeroelastic implications which have been thoroughly discussed elsewhere, and which need not be examined here; by its use, transonic and low supersonic speeds were reached[56]. We now have to face the problems posed by high supersonic speeds; for this régime it seems probable that wings will either have very heavy sweepback (the paper-dart plan form) or will be straight or slightly swept, of small aspect ratio, and very slender. With either type of wing, the body will be long and slender also. Both types of wing are likely to suffer, to a degree not previously experienced, from distortion of the chord of the aerofoil section: an elastic cambering of the wing, with its attendant load and moment changes.

It is unnecessary to emphasise the difficulty of designing very slender wings for the loads they have to bear; from our present viewpoint, moreover, we are more concerned with the calculation of the stiffness characteristics. The problem of determining these characteristics is a far more formidable one than any we have had to face so far. We have a structure which is no longer a thin shell, but is on the contrary in a fair way to becoming solid; the sections can bend, twist, and distort; and the structure is subjected not only to the variations of aerodynamic load arising from these distortions, but also to the thermal stresses arising from kinetic heating.

As regards the latter, it is useful to remember that, roughly, a temperature rise of $(V/100)^2$ degrees Centigrade occurs at the surface of an aircraft travelling at V m.p.h. This is the steady condition; but the important thermal stressing effects arise during the transient period immediately after this speed is reached, when there will be temperature differences of this order of magnitude within the structure. It is during this period that the stiffness problems become most acute.

The thin leading and trailing edges will get hot very quickly after an aircraft accelerates to a high supersonic speed; the thicker centre sections will take longer. In consequence, compression will develop along the leading and trailing edges with a resultant tension in between. An obvious possibility is buckling of the leading and trailing edges. Even if this does not occur, there will be serious reductions in wing stiffnesses.

It was pointed out some years ago by Dryden and Duberg[57] that the elastic torsional stiffness would be reduced by the thermal stresses; if a wing with its leading and trailing edges in compression is twisted, the components of compressive stress which result give a moment in the direction of twist. Cases have been considered where perhaps half the elastic stiffness is lost as a result.

Mansfield[58] and, independently, Kochanski and Argyris[59] have recently pointed out that a loss in bending stiffness of the same order results also. When a wing is bent, there will result an anticlastic curvature of the chord, and if the leading and trailing edges are hot, the resultant compressive stresses have the effect of increasing the bending and the section camber. These effects, moreover, are unfortunately not linear, and are inter-related; we must study them as a whole or not at all.

What, then, is needed? First, a powerful analytical method of treating this problem, which will take account of the simultaneous variation of bending, twist, camber, aerodynamic load, and kinetic heating with its time history. Next, the devising of methods to combat the effects: heat insulation, stress-relieving mechanisms, or the development of alloys of appropriate strength but negligible temperature coefficient such as Invar (Invar itself loses its characteristic property at high temperature and acquires a normal coefficient of expansion).

It seems to be generally accepted that the problems discussed are likely to be the most serious which very high speed will pose[60]; but there will, of course, be many others: to name two only, the structural effects of noise[61, 62] and the aeroelastic problems peculiar to missiles, such as those described by Farrar[63] in his recent lecture to the Society on The Bloodhound. As

regards noise, very high speeds will require very powerful propulsion units, and much energy will be propagated as vibrations into the structure, promoting panel flutter and fatigue. Some of the problems of vibration of the fuselage shell appear monumental in view of the frequency range involved. There seems little doubt that very high speeds will offer a tremendous and fascinating challenge to the aeroelastician of the future.

10. Aerodynamic Derivatives

At the head of this lecture I inscribed two lines from Shelley's "Ode to a Skylark"; I hasten to add that no connection with the fluttering flight of the bird was intended. I have tried to "look before and after" and now reach the subject of which it is fair to say we "pine for what is not." This is a body of data on aerodynamical forces, authoritative and precise in the sense that the forces are predicted by a satisfactory theory and supported by an adequate range of experiment, from which the derivative coefficients necessary for aeroelastic work can be obtained.

I have no wish to belittle the immense amount of work, both theoretical and experimental, which has been progressively increasing throughout the world for the past thirty-odd years. A vast amount of related literature has been presented to the Aeronautical Research Council during the past ten years, and there is no doubt that the position is now immeasurably better than it was during the years of the Second World War. But there are still large gaps; he would be a bold man, for example, who would claim to have studied the aeroelastic stability of a transonic aircraft and to be satisfied that none of the aerodynamical coefficients he had used was in error by (say) 20 per cent.

The difficulty, of course, stems from the fact that a general solution of problems of fluid flow taking into account viscosity (Reynolds number), compressibility (Mach number), and frequency parameter has not been found. Fortunately, in most cases it is known from comparisons of theory and experiment that viscosity effects are not serious, and it is usual to ignore them. However, there are aspects of the aeroelastic problem in which they are important: a case in point is afforded by the calculation of derivatives for tabs, which are often working inside the boundary layer of the main surface. Again, it may well be that viscosity will be important at high supersonic speeds.

For many years, and in many applications, aeroelasticians have used strip theory for calculation of aerodynamic loads; its justification lies in the very reasonable results obtained and, particularly, in the immense simplification it offers. We are now beginning to see our way to a radical improvement on this device, by the calculation of aerodynamic influence matrices: the calculation is a complex one, but is well suited to the use of digital computers.

We may perhaps think of the problem in five phases of aircraft performance: —

(*a*) Low (incompressible) speeds.
(*b*) High subsonic speeds.
(*c*) Transonic (mixed flow) conditions.
(*d*) Supersonic speeds.
(*e*) Hypersonic (including very low density) conditions.

Each of these phases calls for its own technique in a theoretical approach; each needs special equipment for experimental study. As regards the theoretical approach, it has already been remarked that viscosity effects are largely ignored; in addition, it is almost always assumed that the perturbations in the flow are small, so that (for example) shock waves, if they occur, are regarded as weak. This is by no means always justified; it is a fact of experience that the oscillation of shock waves of finite strength can induce instabilities. A promising line of thought to account for finite perturbations is offered by semi-empirical theory, which has already proved fruitful.

One could continue the list of difficulties *ad nauseam*, but to do so would be quite unfair to the very large number of able scientists who are continuously at work on the problem. I had thought originally of mentioning some of them by name, since their work certainly deserves every recognition; but on consideration, I have decided that the task would be exceedingly difficult, and the result invidious. Contributions to this subject have been made from all over the world: the United States, Canada, Australia, Japan, China; while there is scarcely a country in Europe which has not made a significant contribution. I am naturally most familiar with the work being done in Great Britain, and could readily write down the names of two or three dozen workers who have made major contributions to the evaluation and understanding of aerodynamical forces.

I shall conclude, therefore, by mentioning one only: F. W. Lanchester, who before the turn of the century had postulated his theory of peripteroid motion[1], which we now call circulation, and described the action of trailing vortices. By so doing, he provided the basic ideas from which have developed the immense body of work I have been attempting to sketch. Truly, we honour a great man tonight.

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A vote of thanks to the Lecturer was proposed by Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Director-General, Future Systems, Ministry of Supply.

MR. HANDEL DAVIES said they had been privileged to hear a fascinating survey of progress in the field of aeroelasticity from one who had established for himself unquestioned leadership in this field. Professor Collar had, however, been much too modest about his own contribution to that progress. He wished therefore, to remind the audience that many of the advances referred to by the Lecturer owed a very great deal to his own outstanding work.

He would mention only perhaps Professor Collar's pioneering work on the application of matrix analysis to aeroelasticity, his inspiring leadership throughout his time at the Royal Aircraft Establishment during the war, his paper on "The Expanding Domain of Aeroelasticity" at the end of the war, and finally the recent paper in the *Aeronautical Quarterly* of the Society, which would have done credit to any of his younger and more leisured colleagues.

Many of those present would also be aware of his invaluable contribution over many years to the work of the Aeronautical Research Council, and also his tremendous conscientious activities as a Member of Council of this Society.

Everyone would agree that the high precedent set at the First Lanchester Memorial Lecture by Dr. von Kármán had been most excellently upheld by Professor Collar, and he had much pleasure in proposing the Vote of Thanks to him.

THE PRESIDENT, closing the meeting, said how pleased he and the Council were to have Mrs. Lanchester and Mr. George Lanchester present. He asked the audience to respond to the Vote of Thanks in the usual way.

Following the Lecture a Dinner was given by the President and Council at 4 Hamilton Place, at which the following were present:—

Dr. A. M. Ballantyne, T.D., B.Sc., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S., Secretary of the Royal Aeronautical Society. Mr. A. J. Barrett, M.Sc. in A.E., B.Sc., A.F.R.Ae.S., Head of the Technical Department, Royal Aeronautical Society. Mr. A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Chief Executive, Rockets and Nuclear Energy, de Havilland Engine Co.; Member of Council. E. C. Bowyer, C.B.E., Director, Society of British Aircraft Constructors Ltd. Mr. E. G. Broadbent, M.A., A.F.R.Ae.S., Principal Scientific Officer, Royal Aircraft Establishment. Sir Frederick Brundrett, K.B.E., C.B.E., Scientific Adviser to the Minister of Defence. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Honorary Treasurer and Member of Council.

Sir Sydney Camm, C.B.E., F.R.Ae.S., Chief Designer and Director, Hawker Aircraft Ltd.; Member of Council and Past President. Professor A. R. Collar, M.A., D.Sc., F.I.A.S., F.R.Ae.S., Professor of Aeronautical Engineering, Bristol University; 1958 Lanchester Memorial Lecturer; Member of Council. Mr. J. R. Cownie, B.Sc., Grad.R.Ae.S., Chairman of the Graduates' and Students' Section; Member of Council.

Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Deputy Director General, Future Systems, Ministry of Supply; Member of Council. Professor W. J. Duncan, C.B.E., F.R.S., M.I.Mech.E., F.R.Ae.S., Mechan Professor of Aeronautics and Fluid Mechanics, Glasgow University.

Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S., Managing-Director, Vickers-Armstrongs (Aircraft) Ltd.; Immediate Past President and Member of Council.

Mr. H. H. Gardner, B.Sc., F.R.Ae.S., Director and Chief Engineer (Military Aircraft), Vickers-Armstrongs (Aircraft) Ltd.; Member of Council. Air Marshal Sir Charles Guest, K.B.E., C.B., Chief Aeronautical Adviser to the Ministry of Transport and Civil Aviation.

Sir Arnold Hall, M.A., F.R.S., F.R.Ae.S., Director, Hawker Siddeley Group; President, Royal Aeronautical Society. Mr. S. Scott Hall, C.B., M.Sc., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S., Scientific Adviser to the Air Ministry; Member of Council. Dr. D. W. Holder, D.Sc., Ph.D., D.I.C., A.C.G.I., A.F.I.A.S., F.R.Ae.S., Deputy Chief Scientific Officer, Aerodynamics Division, National Physical Laboratory. Mr. H. B. Howard, F.I.A.S., F.R.Ae.S., Director of Structural Research, Ministry of Supply.

Dr. W. P. Jones, M.A., F.I.A.S., F.R.Ae.S., Superintendent, Aerodynamics Division, National Physical Laboratory.

Mr. George H. Lanchester, Brother of the late Dr. F. W. Lanchester.

Mr. P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S., Managing-Director, Bristol Aircraft Ltd.; President-Elect and Member of Council. Sir Harry Melville, K.C.B., F.R.S., Secretary, Department of Scientific and Industrial Research. Mr. M. B. Morgan, C.B., M.A., F.R.Ae.S., Deputy Director, Royal Aircraft Establishment; Member of Council. Professor A. J. Murphy, M.Sc., F.R.Ae.S., Principal, College of Aeronautics, Cranfield.

Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S., Secretary, Royal Aeronautical Society, 1925-51. Professor Sir Alfred Pugsley, O.B.E., D.Sc., F.R.S., F.R.Ae.S., Professor of Civil Engineering, University of Bristol.

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Sir Richard V. Southwell, M.A., LL.D., D.Sc., D.Eng., F.R.S., Hon.F.I.A.S., Hon.M.I.Mech.E., Hon.F.R.Ae.S., Trinity College, Cambridge. Professor A. V. Stephens, M.A., F.R.Ae.S., Professor of Aeronautical Engineering, The Queen's University of Belfast. Dr. G. B. M. Sutherland, F.R.S., Director, National Physical Laboratory.

Mr. W. Tye, O.B.E., B.Sc., F.R.Ae.S., Chief Technical Officer, Air Registration Board; Member of Council.

Sir Owen Wansbrough-Jones, K.B.E., C.B., Ph.D., Chief Scientist, Ministry of Supply. Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Royal Aeronautical Society.

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The Present and the Future*

by

F. R. BANKS (FELLOW)
(Director, The Bristol Aeroplane Co. Ltd.)

Introduction

I would thank you for the honour you have done me by the invitation to give this lecture.

The admiration I have always had for the engineer founder of this famous Derby firm, and the affection for the firm itself from many contacts over the years, both as an itinerant fuel development engineer and, later, as an official in a Government Department, makes this a very pleasant occasion for me.

Through no fault of those whose invitation has brought me here this evening, the time for preparation of the lecture has been relatively short. Quite apart from that, however, I had difficulty in deciding upon a subject, since it is not easy to think of something really new to speak upon openly and freely in aviation—particularly to an audience who will be more or less fully acquainted with any of the subject matter likely to be chosen.

Finally, I came to the conclusion that, as the technical and engineering aspects comprise the everyday work of most of you here, I might more usefully comment upon the present state of the Aircraft Industry and follow this up by some remarks on the future.

In all this cogitating I wondered if I might now be regarded as an "elder statesman" and pondered on the qualifications needed to reach that interesting stage of life, when one freely offers advice and views to his fellow-men whether such are wanted or not!

Everyone, however, comes to learn eventually that advice, however sound it may be, is rarely taken—particularly free advice; since it is often difficult, in the circumstances prevailing at the time, to appreciate whether or not it will prove sound in the long run. And as a famous man once said, "in the long run we will all be dead."

However, perhaps you will allow me on this occasion to give my views—if not advice.

The Present

The Aircraft Industry has been faced in recent years with a much reduced scale of military ordering and considerable contraction; but while this has all been expected and accepted, there has not yet been any official move to plan properly with the Industry its rundown or reduction and settle the nature and scope of its future rôle. In other words, the British Aircraft Industry has drifted along for two or three years with little or no practical guidance or a firm and definite policy from official quarters.

Admittedly, it is difficult, in these days of uncertainty and change, to declare a definite policy and adhere to it; but the present drifting could put the Industry on the rocks and the resultant wrecking would be far more complete than the damage caused by even an indifferent policy. It is also quite unrealistic to expect an Industry, which has been built up over the years as part of the armaments industry, to make a chameleon-like change without Government support to, more or less, industrial status and remain solvent. The enormous man hours' content (the cost) of its products and relatively limited markets make it impracticable for it to provide its own financing, quite apart from the fact that a healthy Aircraft Industry is still needed to provide the means for this Country's defence.

The recent exhortations to amalgamate, combine and consort, can be given practical effect only if the scale of official support, in the form of contracts, is adequate; and if the firms concerned can offer each other complementary technical help and, say, improved testing and manufacturing facilities, rather than the mere duplication and "over-capitalisation" of space and equipment. The necessary finance or financing should also be available to initiate a project and take it to a stage that could be of sufficient interest eventually to receive official consideration and support.

Those optimists who say there is nothing wrong with the Industry and point to the present high level of exports in aviation materiel are apt to forget that, after all, these are largely the result of full Government support in the past for all research and development up to, at least, the production stage.

One important aircraft firm is now entering the civil aviation lists without such official help, encouraged by a good sales run with a very successful aircraft—which, incidentally, had already received Government support at the start for both engine and airframe development. And while it may appear somewhat more easy at the present time to go it alone, since there are some engines available, the basic types of which have been developed under Government contract, the cost of an entirely new engine is almost prohibitive as a private venture, except perhaps for those for relatively small aircraft up to, say, 40-50,000 lb. all-up weight.

The firm in question were virtually forced to go ahead on their own responsibility since, had they just let things drift until their present aircraft ran out of production, they would then have been forced to pay

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off 10,000 or more people. They have decided to take the gamble of making a success of two quite different aircraft types — one a propeller-turbine of about 140,000 a.u.w. and the other a large turbo-jet of over 300,000 a.u.w. But if serious technical difficulties are encountered in the development of early operation of these aircraft, the firm could be so weakened as to affect this Country's position in aviation.

The two countries which lead the World in the size and scope of their respective aircraft industries are America and Russia; but the former has not by any means had to depend upon her large domestic market (representing some 60 per cent of the World's total airline aircraft) to make advances in civil aviation. In fact, Douglas, still the major manufacturer of civil aircraft in the world today, followed by Lockheed and Boeing, largely depends, with these two firms, upon military orders; and Douglas's civil aircraft effort up to the present time is only about 25 per cent of its total.

The cost of the large modern airline machine is proving to be enormous; and when the DC-8 flew for the first time in May last, more than $200m. (£70m.) had already been expended upon its research and development and production tooling.

So, we will only be fooling ourselves if it is thought that the British Aircraft Industry can compete on a private venture basis on this scale. Furthermore, Russia, with her enormous Air Force and fully supported aircraft industry and airline system, must also be considered an eventual competitor in the field of civil aviation. It would seem, therefore, that we should do well to take seriously participation in the European Free Trade Scheme, since it may only be through collaboration with the other European countries outside the Iron Curtain that a balanced economy can be found for the Aircraft Industry.

In the particular case of military aviation: while it is impossible to have numerical superiority, or even equality, with America and Russia, the Royal Air Force must, above all, have equipment of superior quality and performance. Although our bombers are good they are relatively few in number, and there is not yet a supersonic fighter in operational service today.

The dangerous and loose thinking of recent years, putting the guided weapon and ballistic missile prematurely in the position and rôle of the ultimate rather than the complementary weapons, and seeking virtually to eliminate the manned aircraft, is, unhappily, still with us.

It is difficult to visualise a complete metamorphosis from the manned aircraft to the missile since, considering the latter's present state of under-development, it could only at this time usurp the former's position. In fact, so far as one can judge, the manned aircraft and the guided weapon and ballistic missile should all be regarded as complementary to each other.

In any case, should the ICBM and the IRBM eventually replace the manned aircraft, even they will not, in the very long term, prove to be the ultimate in weapons, as the new science of astronautics points the way to more potent methods of warfare. Hence the vital need for the Western Nations to attain the lead in astronautics, at the same time having considerable strength in these weapons and manned military aircraft of high performance.

Incidentally, the ICBM and IRBM will need a very powerful "support industry" for the building of their testing and launching equipment and ground installations—and in providing surface and air transportation for them. The servicing of these weapons will be yet another important consideration since the rundown of National Service may later put the Armed Services in a difficult position in this respect, possibly leading to the hire of technicians from the Aircraft Industry. All this could, however, help to keep the Industry occupied.

Any country depending at the present time solely upon the guided weapon and ballistic missile, with nuclear warhead, is putting great trust in human nature and the deterrent value of the H-bomb, or risks committing itself to a war of complete destruction, since it will have no appreciable strength in alternative and more normal weapons with which to "compromise."

One of the most important Commands in the Royal Air Force today is Transport Command, but it is only of moderate size and is comparatively ill-equipped; and while orders for new transports have been given, these are minimal. Transport Command should be capable of carrying a considerable force to any trouble spot in short time; but it is doubtful, even with the delivery of the new aircraft, whether it will be able to operate as expeditiously and efficiently as it should. In other words, with too few aircraft and the likelihood that some would be scattered at the critical time, with others being overhauled and serviced, there seems to be a need for a more substantial force or bigger reserves, *i.e.* in Army terms, a greater "mass of manoeuvre."

The events of recent months in the Near East must be causing considerable thought on the part of those whose job it is to Plan Ahead; and should these countries and others nearer home, in Central and Southern Europe, object to our use of their air, then long-range and high payload military transports are a must for getting troops and equipment to any trouble spots still farther afield. A glance at a map of the World will show that, in critical areas, an operational range of some 5,000 nautical miles is likely to be required. Even in helping to keep the peace nearer home it might be necessary to fly deep into Africa and then out again, on a kind of dog's leg course, in order to deliver war materiel without political repercussions en route.

If, therefore, the Middle East countries were to bar us over-flying them with military aircraft and equipment, as I think they will, then there is an immediate need for a 5,000 nautical mile "Commonwealth Strategic Freighter," carrying a payload of 15-20 tons and powered with four 7,000/8,000 h.p. propeller-turbines. Shades of the Orion!

I strongly suspect that such a freighter and troop carrier could be approved and built if there were agreement, by a measure of compromise, between the Royal Air Force and the Army. The fact that the former's

equipment has largely been designed for air-freighting whereas the latter's, by its sheer weight and bulk, is only suitable for surface transportation is, probably, the chief cause of the difficulty in formulating a common air transport requirement. But this failure to compromise, and lack of realism, is very weakening to the Nation's military purpose.

Some may think this lecture, so far, has rather a political bias; and indeed it has. The simple reason is that the Aircraft Industry, which was created and built up in war and because of threats of war, has so greatly raised this Country's engineering strength and prestige in the World that it is not possible to ignore the political angle when the Industry's future is at stake. In fact, as previously stated, wrong thinking on the part of those in high places could lead to an indiscriminate rundown of the Industry and eventual engineering bankrupicy.

To reiterate, if we cannot have numerical preponderance or even equality with the Air Forces of America and Russia (and, incidentally, China, which probably has the third largest Air Force in the World), we must

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Personally, I cannot foresee any new or far-reaching developments in gas turbine technology during the next decade, although there will be greater recognition of the need for improved operating economy and reliability which may lead to the further encouragement of the low temperature turbo-jet, the by-pass and also the ducted fan. But while these engine types will probably give what is expected of them in specific fuel consumption on the test bed, they have eventually to prove themselves in flight. Their larger diameter and, therefore, increased "drag" could possibly vitiate in airline operation the gross improvement in test bed fuel economy.

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an industry, after allowing it to run down, is always vastly greater than it otherwise would have been in keeping it compact and healthy by an imaginative research and development programme and realistic procurement.

It is admittedly difficult for an Air Staff to make up its mind on the right things to order, since the (paper) choice of aircraft and advanced weapons is now very wide and their development exceedingly costly; all of which leads to delay (possibly due to Treasury resistance) and to the best becoming the enemy of the good — the council of perfectionism too often prevailing.

Whatever the outcome regarding the manned aircraft versus the guided weapon and ballistic missile, the orders for military aircraft are going to be exceedingly small in number and it is obvious that the engine industry of this country must contract. It is, however, desirable to have two major manufacturers so as to provide some measure of competition and steady improvement in quality, and also to ensure availability of a variety of types.

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Engine Sales Technique

The art or business of selling an aero-engine has changed and advanced in recent years and considerable skill and knowledge, together with very hard work, are now needed to get an engine accepted by the aircraft manufacturer and, also, the operator. Further, as previously indicated, the sale or rejection of an engine is much more critical to its builder at this time than ever before, since, with so few new requirements, it can represent either a major gain or a major loss of work in the years following. In addition, the accepted engine will steadily accumulate running hours and much experience for those concerned, making the chances of other competing firms still more remote when the next opportunity to meet a new requirement comes along.

It is no longer possible to sell engines on the "old boy" basis or to make a deal "over the bar room counter." In fact, it demands the unremitting effort and [illegible] these are minimal. Transport Command should be capable of carrying a considerable force to any trouble spot in short time; but it is doubtful, even with the delivery of the new aircraft, whether it will be able to operate as expeditiously and efficiently as it should. In other words, with too few aircraft and the likelihood that some would be scattered at the critical time, with others being overhauled and serviced, there seems to be a need for a more substantial force or bigger reserves, *i.e.* in Army terms, a greater "mass of manoeuvre."

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To reiterate, if we cannot have numerical preponderance or even equality with the Air Forces of America and Russia (and, incidentally, China, which probably has the third largest Air Force in the World), we must at least be sure of superiority in the quality and performance of our equipment. And had it not been for the unique Strategic Air Command (S.A.C.) of the U.S.A.F. the Western World would have had little bargaining power in the past decade.

Engine Status

I have said on a number of previous occasions that the exceedingly rapid evolution of the gas turbine, from the original Whittle concept to the engines of today, is very largely the result of many years experience and concentrated effort on the development of the piston engine; which effort resulted in considerable know-how and new and improved materials and manufacturing techniques.

It is also probably true to say that the gas turbine is now in a similar state of development as was the piston engine at the start of the Second World War—where it is largely a matter of, " paying your money and taking your choice " to get the required engine. But since the cost of developing a new gas turbine is so enormous and the market relatively limited, it is difficult to see how this can be done without Government assistance. I refer of course mainly to civil engines, since military types are usually paid for by the Department concerned; although there is now a somewhat cheese-paring and short-sighted outlook which is resulting in too little official support for those military engines that have some civil application, and vice versa.

The cost of designing and developing a 15,000 lb. thrust turbo-jet to the initial production stage is somewhere between £10m. and £15m., which can be even further increased, towards £20m., in the case of its civil application by the sheer bench and flight time now expected before the engine is accepted for regular airline service.

The comparatively rapid maturity of the aviation gas turbine, coupled with the diminishing military outlet, has left those engine manufacturers at present in the lead in a dominating position. Therefore, apart from small propeller-turbine and jet engines of, say, 1,000 h.p. and 2,500 lb. thrust, and suchlike, of which there are quite a number coming along here and in the United States of America, it would seem that the present leaders in engines of important size are likely to hold their position for some time to come.

Personally, I cannot foresee any new or far-reaching developments in gas turbine technology during the next decade, although there will be greater recognition of the need for improved operating economy and reliability which may lead to the further encouragement of the low temperature turbo-jet, the by-pass and also the ducted fan. But while these engine types will probably give what is expected of them in specific fuel consumption on the test bed, they have eventually to prove themselves in flight. Their larger diameter and, therefore, increased " drag " could possibly vitiate in airline operation the gross improvement in test bed fuel economy.

Due to Mach number limitation, greater thrust could only offer improved take-off and rate of climb—which might nevertheless be worthwhile; but if a reduction in specific fuel consumption of somewhere between 10 and 15 per cent were possible, and the cost of re-engining did not outweigh this improvement, such a course could result in improved profits or, perish the thought, cheaper air travel. In this connection, it is significant that two of the leading American engine manufacturers are also developing by-pass and ducted fan engines—or turbo-fans as they are known in the States.

At the other end of the scale, and well capable of being developed as a private venture, is the need for a small propeller-turbine of 250/400 h.p. for agricultural (crop spraying) aircraft, for world-wide operation in all climates. Such an engine should be robust and capable of being serviced in the field and must sell for £2,000/2,500 a copy, without propeller. This is a challenge to a clever design team.

We now have no monopoly in the aviation gas turbine, with America and Russia building these engines in their thousands compared with our hundreds. But they, in turn, have no monopoly in quality, and the British engine manufacturer is well able to build high performance engines of low weight comparable with, and probably superior to, any in the world today. This superiority has been made possible largely by the Government support given in the form of research and development contracts over many years. Therefore, if there is serious curtailment because of drastically reduced military needs our standing in aviation is bound to suffer, with the scope and rate of civil aviation development also adversely affected.

It is probably true to say that no Government, whatever its political colour, has ever " been good " to the Aircraft Industry. Most have been short sighted and dilatory, and only when it was necessary to re-arm because of the threat of war has adequate support been, of necessity, forthcoming. But the cost of building up

an industry, after allowing it to run down, is always vastly greater than it otherwise would have been in keeping it compact and healthy by an imaginative research and development programme and realistic procurement.

It is admittedly difficult for an Air Staff to make up its mind on the right things to order, since the (paper) choice of aircraft and advanced weapons is now very wide and their development exceedingly costly; all of which leads to delay (possibly due to Treasury resistance) and to the best becoming the enemy of the good —the council of perfectionism too often prevailing.

Whatever the outcome regarding the manned aircraft versus the guided weapon and ballistic missile, the orders for military aircraft are going to be exceedingly small in number and it is obvious that the engine industry of this country must contract. It is, however, desirable to have two major manufacturers so as to provide some measure of competition and steady improvement in quality, and also to ensure availability of a variety of types.

Although the three or four basic engine types (the propeller-turbine, the turbo-jet, the by-pass and, possibly, the pure ducted fan) will be with us for some years, it is difficult to visualise a need for, say, a propeller-turbine of 12,000 h.p., an example of which is already operating in Russia. But, maybe, this is only anticipating the future. Also, while it is quite practicable to build very large jet engines well in excess of 20,000 lb. (dry) thrust, it would seem more economical of effort to use a greater number of the "smaller" units for a desired total thrust—except for (single engine) supersonic military fighters and interceptors.

With the Industry today facing the toughest competition in its history, and no quarter given in order to land an order, the selling pressure is particularly high for engines for civil aircraft; since the acceptance of an engine for this purpose virtually guarantees continuing business for the manufacturer concerned, assuming an aircraft operating life of ten years and, perhaps, in the case of the large jet machines, fifteen years. Further, for every engine installed in a civil machine, the engine builder can be assured of selling the equivalent of two or three other engines in the form of spares and replacement parts during the life or obsolescence of the aircraft, although this could be a reducing value with increasing engine life; and 2,000 hours between overhauls is now with us. But there is always the question of certain expensive components not quite lasting out to the next overhaul period, and having to be replaced in the previous period at considerable cost.

The interesting fact that has emerged with the gas turbine in airline service is its inherent reliability. It took many years before the piston engine was able to operate for a thousand hours between overhauls, whereas the propeller-turbine reached and exceeded fifteen hundred hours well within two years of operation. The gas turbine is, happily, largely free from the frictional and cooling problems of the piston engine, and has no continuously operating electrical ignition system which, because of its environment and working conditions, has always been a constant source of operational unreliability.

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It is no longer possible to sell engines on the "old boy" basis or to make a deal "over the bar room counter." In fact, it demands the unremitting effort and attention of everyone from the managing director downwards to sell an aero-engine today; and even if one engine appears to offer somewhat better performance possibilities than another, the choice may not necessarily fall upon the former. Since, although it must naturally give the required performance when built, the successful engine may have been chosen because of better sales strategy and tactics, more running background of the basic engine type or the greater experience and reputation of its manufacturer—all leading to a progressive build-up of customer confidence.

While these points refer more particularly to selling a civil type aero-engine, they differ but little in the military case except, possibly, in regard to the greater degree of latitude generally allowed in the matter of engine delivery and the date of roll-out of the aircraft; which may have a variety of (military) rôles to satisfy and, unlike the civil aircraft, does not normally operate (except in war) to a strict schedule almost immediately upon delivery. The military engine will also be running at a higher specific rating than that of its civil counterpart, which might necessitate more coaxing or development to get; although this is now likely to be over-shadowed by the sheer number of bench and flight hours required before the somewhat lower-rated civil engine is certified and accepted, since it is expected to start life with a reasonably long running period between overhauls—at anything from 500 to 1,000 hours.

Engine weight, like aircraft structure weight, is a most important factor in the operating economy of an aircraft; and it should generally be possible to effect some reduction in the civil version of a military engine, particularly as the former will be operating at a somewhat lower rating and is not normally subjected to the same manoeuvring loads.

Quite a remarkable change in the engine/aircraft picture has occurred since the Second World War. Before and during the War, the time taken (4-5 years) to design and develop the piston engine and get it through the flight stage to initial production was greater

than that absorbed in designing and building the aircraft (airframe). Today, the position is reversed and the aircraft takes as long, or even longer, to get to first flight than the engine.

Because of the large difference in time between engine and aircraft development and manufacture in the piston engine era, the aircraft was designed around an existing engine; but, nowadays, the engine has most likely to be designed to fit the aircraft, if there is no suitable power unit already available. And since the first cost of both engine and aircraft is so great, the former may not get started until the contract for the latter is landed.

For a new civil engine, about 10,000 hours of test bench running and some 5,000 engine flight hours are desirable—with 10,000 hours as the target. But the provision of suitable flying test beds is not getting any easier and, with engine and aircraft design starting at the same time, it is becoming more difficult to accumulate a large number of flying hours before the aircraft proper is built.

Luckily, the gas turbine does not appear to require the considerable background of operating hours normally needed by the piston engine, to establish a fairly high degree of operational reliability. This should not, however, be confused with the effort needed to get a new engine to that stage, since its development is always time-consuming and costly.

A further word on selling aero-engines. While every engine company has its performance engineers, experience suggests that this group can with benefit be enlarged sufficiently to help cover sales activities; so that selected members may accompany the senior officers of the firm on a sales drive without causing interruption and delay within the firm when they are absent for extended periods. The further advantage in having this sufficiency of performance engineers is that some, due to their inclinations and personalities, can become good technical salesmen and company representatives in their own right.

The Future

It is plain that while the gas turbine in its various forms will continue to be built for many years for the propulsion of more or less conventional aircraft, the engine builder must be prepared to launch out in other directions and develop more exotic power units. But it should be appreciated that the rocket motor, for instance, although costly, is no substitute in technical or production man hours for the gas turbine engine.

In this connection it is interesting to note what is happening in the aviation and allied fields in the United States today, where those concerned are now looking farther ahead and becoming "space cadets" in anticipation of, and in preparation for, the exploration of outer space—sometimes, it may be thought, to the detriment of more immediate and profitable activities. But, whatever the problems, the rapidity with which research into hypersonics and space techniques (astronautics) has progressed, together with the investigation of all the possible propulsion methods, is remarkable.

The term "astronautics" is not always properly understood. Academically speaking, it comprises a number of different sciences and technologies such as, higher ballistics, celestial mechanics (an advanced form of study of gravitational effects and orbits, etc.) and the development of various possible propulsion systems. In practice, the ICBM represents the lower limit in astronautics and from there they progress through glide vehicles, such as the U.S. Dyna Soar project, satelloids (which are put into lower orbit than the satellite and are kept going with periodic bursts of power) and orbitals (satellites or sputniks), all of which lead towards the probe vehicle and then the "spaceship" of the future. The orbitals include "recce" and observation satellites and "jump-down" weapon systems, and so on.

The Lewis Flight Propulsion Laboratory* at Cleveland, which was created with very elaborate research and test facilities for the gas turbine era, anticipating a long evolutionary period, is now actively planning to use these various facilities for research into new forms of propulsion, leaving only about a twenty per cent availability for such *ad hoc* work on gas turbines as may be demanded by the Armed Services and the Industry; eighty per cent of the establishment and facilities being split, according to needs and progress, between nuclear propulsion, rocket motors and such things as ion rockets and plasma jets, and so on.

I cannot, personally, get enthused about the usefulness or practicability of nuclear energy for aircraft propulsion, except for very special military purposes yet to be defined; but I have little doubt that both America and Russia will, sometime soon, demonstrate a turbine-propelled aircraft having a nuclear source of energy. The flying boat would appear to offer a practical means of trying out this method of propulsion, since there is less risk of contaminating populated areas in the case of a mishap.

Presumably, nuclear energy will be used more or less directly to provide large amounts of heat at very high temperature for rocket propulsion or for electrical generation for ion rockets and plasma jets.

The Supersonic Air Liner

The next practical step in aviation in its more normal ("steam aviation") form will be the supersonic air liner, the development of which will involve considerable time and effort and enormous cost. The building of such a machine would, however, have to be completely Government supported so far as this country is concerned.

The leading American manufacturers appear already to be scheming supersonic aircraft, despite the nervousness, now becoming apparent in some quarters, about the operating economy of the large subsonic jet machines when they come into service.

There is, in this country, a Committee (Supersonic Transport Aircraft Committee) composed of members of the Government Departments concerned and the Industry, which has been investigating the problems associated with the development of the supersonic

*Now N.A.S.A. Lewis Research Center.

passenger aircraft. But since the Committee is only advisory its deliberations may continue for some time, and any advice that it might then tender could well be out of date or misleading to an original thinking design team.

The whole effort appears too leisurely if it is really intended to consider seriously the supersonic air liner and back it nationally.

If, however, Transport Command and the Army decided that a supersonic troop carrier was an urgent need and, with all the help available, were able to issue a requirement within a year, that might give the start needed for this country to indulge in supersonic transportation.

The leading question on the supersonic passenger aircraft is, "how supersonic should it fly?". A Mach number of 1·3 seems hardly worthwhile, since the advantages and time-saving in flying from A to B, over the high subsonic jets now building, are not sufficiently great to warrant the enormous effort and cost. Therefore, the aim might be $M=2$. But having in mind the proper timing for its introduction, and the fact that those concerned in the U.S.A. are considering still higher speeds, it is more likely that a Mach number of 3 will be the chosen speed.

Recent statements by senior executives of the leading American aircraft manufacturers have suggested that such a machine could be designed and built and ready for first flight in about two-and-a-half-years! While this time factor should be doubled or trebled for practicability's sake, the load at present being carried by the firms building the large subsonic jet aircraft, together with the fact that the airlines buying these machines have yet to bring them into service, makes it most unlikely that the supersonic aircraft would be acceptable to anyone much before 1970. Indeed, I would suggest fifteen years from this date for its introduction into airline service at a minimum cost of £100m. for research and development and the provision of production tooling.

In their early appraisal of the supersonic air liner, certain designers apparently considered the lower supersonic speed (of a Mach number of 1·2 or 1·3) to be the more practicable on account of obtaining a reasonably good L/D; and while an L/D of somewhere between 16 and 18 will be achieved by the DC-8 and Boeing 707, it was thought not so long ago that half this value would hardly be possible at a Mach number of 2. More recently, however, it has been suggested that an L/D of 7·5, and even higher, might be achieved at $M=3$ provided that both fuselage and wing formed an aerodynamic and lifting entity, with no excrescences and with completely buried engines, then making possible a still-air range of somewhere between 3,000 and 5,000 nautical miles at, say, a design cruising speed of about $M=2·7$-3 at between 70,000 and 80,000 feet—with a payload of about 7 per cent.

The economic problem of the supersonic aircraft concerns the increasing ratio of fuel to payload carried —fuel being the greatest direct cost factor in airline operation.

In this connection, while it is perhaps dogmatic to eliminate the borane fuels as too costly to produce in adequate quantity for civil aviation, and too difficult to use in a turbine engine, they might possibly find favour in a $M=3$ bomber having mixed power plants. Such fuels could be burned in a ram-jet and an afterburner without the clogging troubles experienced when using them in the normal way and ahead of the turbine wheel, and their use would tend materially to reduce the size and weight of the aircraft. However, my personal opinion is that these particular fuels will not find favour due to manufacturing cost and operational limitations.

In regard to mixed power plants: it is the view of Bristol-Siddeley Engines that the combination of the turbo-jet and ram-jet offers the optimum solution for supersonic travel at about $M=3$ at between 70,000 and 80,000 feet. Their calculations have shown a consistent pattern. At a cruising speed of $M=2$, the total engine-plus-fuel weight for the turbo-jet and ram-jet combination, expressed as a proportion of the all-up-weight at take-off, is about the same as that for an unreheated turbo-jet. At higher Mach number, the turbo-ram-jet shows an increasing advantage over the turbo-jet, the total weight needed for the former and its fuel decreasing with increasing Mach number compared with a sharp increase in the weight of the turbo-jet and its fuel.

Personally, I think one of the biggest obstacles to the operation of the supersonic machine will be the "sonic bang"; and quite how this will be overcome is not at all clear at the moment. Possibly this might limit supersonic travel to long over-sea crossings with subsonic let-down on the approach.

VTOL and STOL

When considering the supersonic passenger machine, the question of the benefits of vertical take-off and landing (VTOL) or short take-off and landing (STOL) naturally arises; but the additional development effort and time needed to bring these features to a safe and practical state would add considerably to the already formidable problems facing the designer and manufacturer. It seems, therefore, more practicable first to try them on a military transport or a bomber, particularly if they are of the multi-engine integrated design proposed by Dr. Griffith. In any case, an aircraft designed to fly at a Mach number of 3 at 70,000 feet should have sufficient power for take-off on the runways already being made available to the large subsonic jet machines.

One of the most important considerations in the design of future transport aircraft will, I think, concern the engine installation or, specifically, the position of the engines relative to the primary airframe structure, since it is already apparent that the licensing authorities in this country and in the U.S.A. are becoming very occupied with the consequences of turbine blade and disc failure.

Surrounding the turbine casing with dense or resilient material, while resulting in some increase of

weight, may not necessarily provide the required degree of safety; and buried engines and engines in pods, which are close or immediate to primary structure, will always represent a potential hazard. Therefore, it would seem that the only entirely safe place for the engines is at the back of the aircraft, mounted or cantilevered from the rearmost primary structure and, if practicable, well spaced from each other; which probably means going to a "canard" or tail-first design, since this (as distinct from the conventional aircraft with engines mounted at the rear of the fuselage) will avoid critical c.g. position and also the danger of an engine entering or crushing the cabin in the event of a crash.

Conclusion

I have, perhaps, tried too hard to make clear the obvious: that the Aircraft Industry cannot in future expect to remain at its present potential. But it is a national characteristic or trait that impels, or compels, some members of the Industry to be somewhat unrealistic in accepting the facts of life. And it is this lack of realism, coupled with just sufficient official support to keep the flywheel turning, which lulls those who indulge in daydreams, of the glorious past and optimistic future, into a false sense of security or a state of unwarranted self satisfaction.

With their limited domestic outlets, none of Western Europe's aviation industries can indulge in the development of large civil aircraft or their engines without Government support; and the choice of other work is likely to be very restricted unless the necessary finances are available to provide the tools and tooling for the manufacture of something considerably more prosaic—with, of course, the inevitable break up of invaluable technical teams.

So far as the British Aircraft Industry is particularly concerned, it must be assumed that, despite the apparent lack of realism displayed in official quarters, it would be the national wish to keep the Industry strong and competitive in both the military and civil fields—although the happenings of recent years have rather smacked of subterfuge, with the attempts to keep the Industry going on a shoestring.

Positive Government support should allow a compact and healthy Industry of between 150,000 and 200,000 people, excluding the electronics industry. We simply cannot afford at this critical period to be "out on a limb," or have little or no part in those advances in flight and space technology which will be made in the not so distant future.

On the other hand, and assuming Government help, the Industry must see clearly the markets ahead and cater for them, which can only be done by market research of a high order.

It is very important to keep our World position in the aero-engine field, but this can only be done effectively with a continuing need for military aircraft and one or two officially supported civil types.

Participation in the European Free Trade scheme offers some hope for the combined aviation industries of Western Europe, always provided that the goodwill is there and funds are not wasted on the duplication of projects; and this country is certainly in the best position to act as the supplier of aero-engines to our European friends.

To those who wish to read into the words "full Government support" a cry for the nationalisation of the Industry, I would point out that the plea here is for rationalisation and official support of a precious industry to keep it healthy and active. Nationalisation would tend seriously to react against the foreign sales' effort. In any case, there would be little object in nationalising an industry which, unlike the basic industries, is not so very large when the enormous man hours' content of its products is taken into account.

Having pointed out the dangers of drift, I have the uncomfortable feeling that the progress of the guided weapon and ballistic missile is suffering similarly and is in a state of dither.

In my view, the whole business of aviation and astronautics, viewed from all (military and civil) aspects, demands the undivided attention of one specialising Ministry or Authority, which is not to be expected of the present set-up as between the Ministry of Supply and the Ministry of Transport and Civil Aviation. I would suggest, therefore, the formation of a Ministry of Aviation and Astronautics, to handle everything to do with aviation and space flight, controlled by a strong and broad-minded Minister of Cabinet rank.

As I have said on a number of previous occasions, it is my firm belief that research and development budgets should cover five years rather than the present yearly period—the former span being more representative of the time factor in engine and aircraft development. But there is obviously no reason why there cannot be a yearly progress review, with re-assessment as necessary.

To reiterate: the continual and continuing delay in making up the official mind on the future pattern of air armaments could wreck the aviation effort of this country and eventually weaken, almost to the point of death, the Aircraft Industry. While delay avoids the immediate spending of funds it does not lead to any saving, since it allows the competitor or adversary to gain an overwhelming lead which requires very costly effort even to draw level. The delays and hesitations of recent years have, in fact, been a horrid waste of time and money, and with military weakness comes loss of World stature and prestige.

Acknowledgments

Finally, I wish to thank The Bristol Aeroplane Company Limited and Bristol-Siddeley Engines Limited for permission to give this lecture, and Mr. M. N. Golovine for his valuable help and advice. My thanks also go to my secretary, Mrs. Hillier, for the numberless times she has to retype any and all of my talks.

Notes on Air Breathing Engines for Supersonic Flight*

by

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1. Introduction

Aircraft operate within a domain of altitude and Mach number, the limitations to which are prescribed by the present state of technical knowledge. With the perfection of the aircraft gas turbine we have witnessed the boundaries of flight recede beyond the sonic barrier and are now approaching the stage where the vastly improved propulsion technique will permit cruising supersonic flight. Several excellent papers referring to this subject have been given[1,2,3].

The boundaries of aeronautical achievement are apparent in the World's Records for altitude and speed, beyond which man has not yet passed. There is a sure proof that present limitations of flight are but temporary in the tremendous human effort which is applied to the problems holding up further advance into the unknown.

Figure 1 is based on an American report of 1953[5], which deals with the limitations of air breathing propulsive systems and translates typical material and combustion limitations into the more familiar terms of forward speed and altitude. It is seen that the assumed conditions result in a maximum speed of $M=3$ for the turbo-jet at altitudes up to 150,000 ft., while for the ram-jet we have a maximum of $M=4{\cdot}2$ at 170,000 ft. With its simpler construction the ram-jet's material problem is less severe and a speed advantage over the turbo-jet is obtainable. On the other hand, without mechanical compression there is a more severe combustion limitation which restricts the ram-jet in its high altitude behaviour.

Along with the fundamental problems in materials and combustion at the frontier of knowledge there is a host of equally severe but more mundane difficulties associated with supersonic flight. For example, consider the question of reserve fuel. Fig. 2 shows the proportion of all-up weight required for the reserve fuel against the lift/drag ratio of the aircraft and specific fuel consumption, on the assumption that a half-hour's supply is required. In this example we may have taken too long a time for the reserve of a future supersonic aircraft, or too low a lift/drag ratio, or too high a specific fuel consumption. With typical figures in mind this graph seems to point out an acute problem of the very high speed aircraft.

*A lecture given to the Luton Branch on 1st May 1957. Revised April 1958.

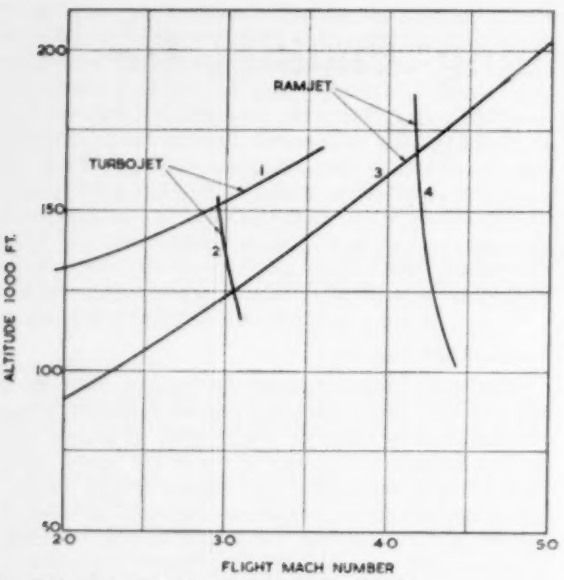
2. Engine Forms

The basic construction of the straight turbo-jet is well known. This engine can provide a take-off thrust of three or more times its own weight. It gives a substantial increase of thrust with forward speed when fitted with a suitable intake and exhaust nozzle. Further, the minimum specific weights are attained in units of suitable size. As a type, it is robust, simple, economic in fuel and has great possibilities of future development. The simplest form has a single spool rotor, Pitot intake and convergent fixed nozzle.

In the supersonic field both thrust and fuel consumption of the turbo-jet are adversely affected by present-day temperature limitations. Internal cooling would postpone the difficulty, but is too expensive and too elaborate. With increased forward speed, the available heating range of the working fluid between compressor exit and turbine inlet becomes smaller and smaller, until it is so reduced that the cycle losses play a disproportionate part and seriously cut down the thrust and efficiency. This effect eventually causes the final fall off in performance of the turbo-jet at high Mach numbers, but has been successively postponed as succeeding generations of engines have advanced in component performance.

When reheat is applied to the turbo-jet, the thrust rating is increased at the cost of fuel consumption without increasing the loads on the compressor and turbine. In the turbo-ram-jet the reheat has been developed to the stage where it is regarded as the main thrust-producing component. The compressor turbine serves to increase the pressure in the reheat chamber at low speeds where the ram by itself would be insufficient. To cruise economically as a simple jet engine, as well as operate on reheat, a variable area final nozzle is required. Reheat has its problems and yields diminishing returns as turbine temperatures increase. Nevertheless it is the simplest way of boosting the turbo-jet for the thrusts required.

An interesting form of the turbo-ram-jet has been suggested which has a contra-rotating supersonic compressor and turbine[6]. In this motor the rotating parts are reduced to the bare minimum for the pressure ratio required. Each rotor stage consists of a single row of blades and compression is obtained by the very high relative velocity between the stages. In theory this motor can only operate if the speeds are controlled in such a way that the Mach number pattern throughout



1. Turbo-jet combustion ceiling $P_{cc}=0{\cdot}1$ ATM.
2. Turbo-jet compressor temperature limitation 560°C.
3. Ram-jet combustion ceiling $P_{cc}=0{\cdot}1$ ATM.
4. Ram-jet air inlet temperature limitation 1100°C.

FIGURE 1. The effect of limits in the technology of materials and combustion upon altitude and flight Mach number of the turbo-jet and ram-jet.

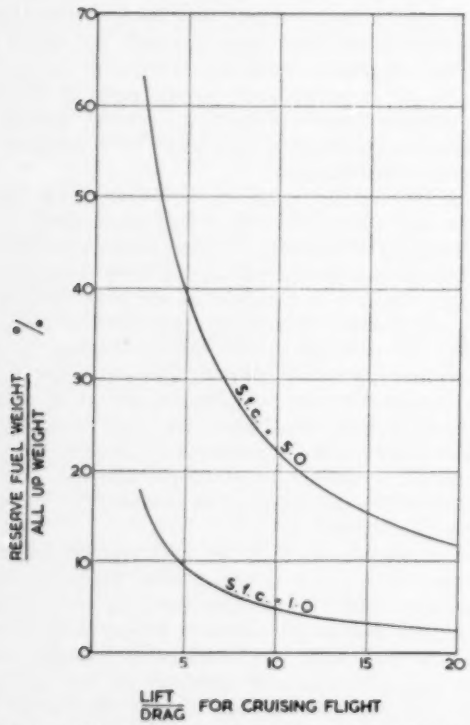


FIGURE 2. Ratio of reserve fuel weight to all-up weight for half hour cruise of supersonic aircraft.

the rotor does not change. This means that the rotational speed must vary as the square root of the local absolute temperature. Thus although the construction has simplicity it has very little flexibility. A variable area final nozzle is required if it is to operate both with, and without, reheat.

With the compressor deleted altogether, the engine becomes a ram-jet. Fig. 3 shows a double-cone type intake, a zoned combustion system and a variable plug type convergent-divergent nozzle. The motor is limited to, but in some ways is ideal for, the supersonic field.

Figure 4 indicates a by-pass jet engine which is a potential supersonic engine by virtue of the large reheat capacity in the two exhaust streams. Without reheat this same engine has good fuel economy, particularly in the transonic field. The turbine design permits the rotor to compress a relatively large quantity of air into a low pressure by-pass stream. Reheat may be applied to this stream separately, before it is discharged to the main exhaust, or it may be applied to both streams after they have mixed together before the final nozzle. Not a great deal is known about the problems of the by-pass engine in supersonic flight for its design, both aerodynamic and thermodynamic, is relatively complex. There is a wide choice of design data to be explored both as regards by-pass flow ratio and the pressure ratios to be employed. In the simplest case, with a by-pass pressure ratio of unity the engine takes the form of the straight jet in which air is bled from the intake ahead of the engine compressor face and ducted round the combustion chamber and turbine, either into the reheat chamber or to act as an ejector for the final jet, thus using the supersonic intake as the compressor for the by-pass and the discharge as a means of enhancing the performance of the final nozzle. More generally a two-spool construction would be used with the by-pass compressor boosting the main compressor. A variable area convergent nozzle would be required.

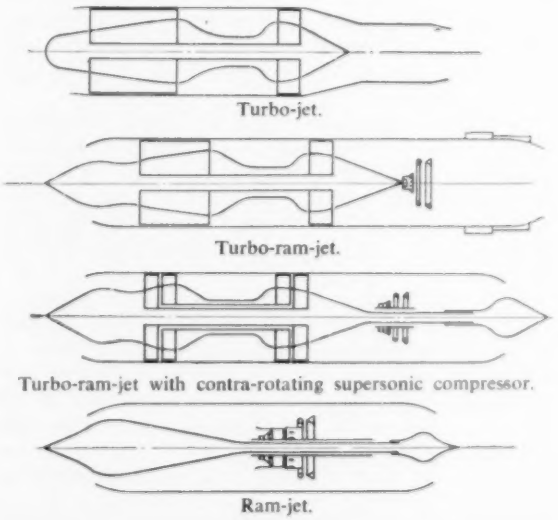
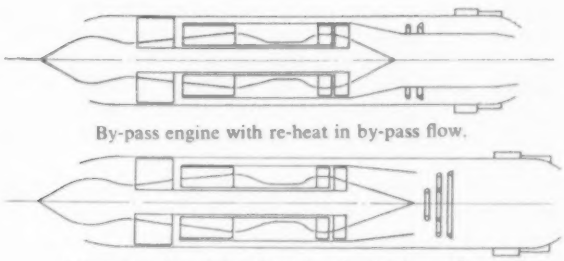


FIGURE 3.



By-pass engine with re-heat in by-pass flow.

By-pass engine with re-heat in mixed exhaust flow.

FIGURE 4.

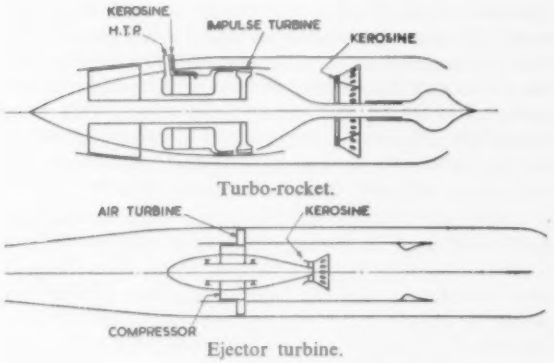


FIGURE 5.

Figure 5 indicates a turbo-rocket engine which, although not entirely an air breather, becomes one in cruising supersonic flight when the separately driven high pressure turbine is closed down and the compressor windmills. Thus in high speed cruise the engine operates more or less as a ram-jet and has a similar performance. With the turbine in action the thrust is boosted considerably because the air throughput increases. The turbine also makes it possible to obtain thrust under low speed conditions, thus overcoming one deficiency of the ram-jet. The total fuel consumption under turbine operation is heavy because the oxygen requirement for the high pressure gas turbine is provided from the aircraft tanks in liquid form and not by the atmosphere. A variable-area, convergent-divergent nozzle is required.

The lower half of Fig. 5 is of the ejector turbine[6] where a low pressure compressor supplies a primary combustion chamber the discharge from which acts as an ejector to drive the air turbine. The air turbine drives the compressor and makes the cycle self-sustaining. This type of engine is known to have possibilities at transonic speeds and low supersonic speeds with a simple Pitot intake and plain convergent nozzle. There is no turbine temperature limitation, which is a big advantage; but unfortunately it has no static thrust.

Figure 6 gives some estimates of thrust performance of various possible engines as made from sketch designs. The corresponding s.f.c.'s are marked on the curves, the units are lb./lb. thrust/hr.

3. The Intake

Besides metering the air to the engine the supersonic air intake performs the major part of the compression in the turbo-jet and the entire compression in the ram-jet. As Mach number rises the pressure ratios obtainable from intake ram rapidly exceed those of the most efficient multi-spool compressor. For example, at $M=2$, the ratio of total to static pressures in the approach air stream is 7·8, at $M=2{\cdot}5$ it is 17·1, and at $M=3$ it is 37. These pressure ratios would be available between the ambient static atmospheric pressure and the total pressure at the engine face if the intake could be made to function ideally, *i.e.* 100 per cent efficiency, without any loss of total pressure.

Up to the present time the most successful forms of supersonic intake are those in which practically all the supersonic compression is done through a system of external oblique shocks. The shocks are usually initiated by a forward facing spike or wedge or, in a three-

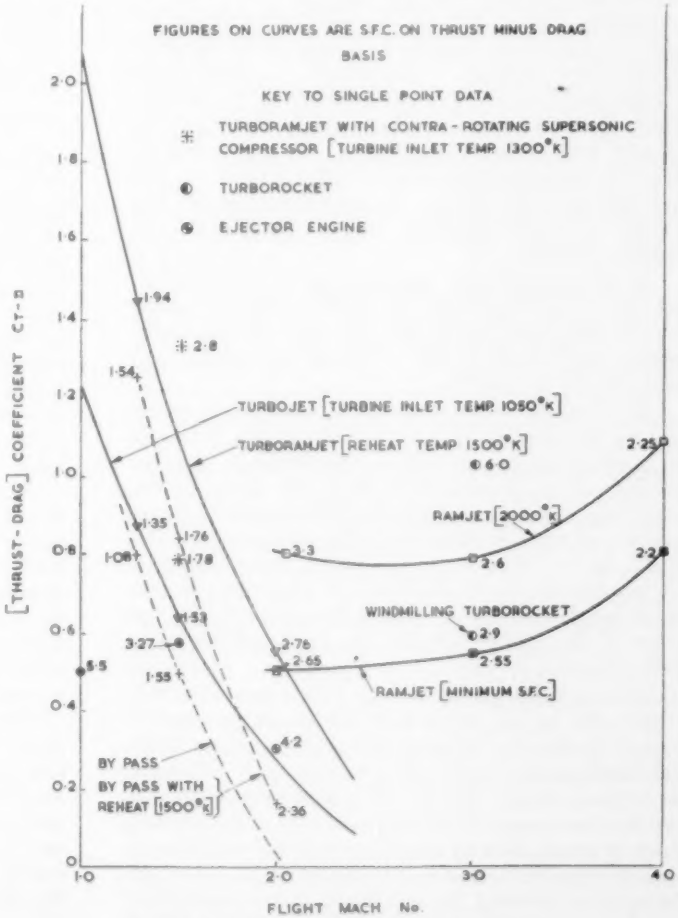

FIGURES ON CURVES ARE S.F.C. ON THRUST MINUS DRAG BASIS
KEY TO SINGLE POINT DATA
TURBORAMJET WITH CONTRA-ROTATING SUPERSONIC COMPRESSOR [TURBINE INLET TEMP 1300°K]
TURBOROCKET
EJECTOR ENGINE
[THRUST-DRAG] COEFFICIENT CT-D
TURBOJET [TURBINE INLET TEMP 1050°K]
TURBORAMJET [REHEAT TEMP 1500°K]
RAMJET [2000°K]
WINDMILLING TURBOROCKET
RAMJET [MINIMUM S.F.C.]
BY PASS
BY PASS WITH REHEAT [1500°K]
FLIGHT MACH No.

FIGURE 6. Performance of various power plants.

dimensional intake, by the apex of a cone forming a centre body in the intake opening which thrusts forward, compressing the oncoming air. This system has the advantage that oblique shocks are relatively efficient, while the forward centre body ensures that practically all supersonic compression is done before the air passes into the intake, thus cutting down the weight and space required within the power plant.

With any form of intake, air can only be captured and compressed by the expenditure of energy, which is a charge against the power plant. When the compression is external any air approaching the power unit which is spilled over the lip into the external flow instead of entering the engine after being partly or fully compressed by the external shock system, is wasteful drag. In other words it is necessary to ensure that the intake matches the engine air demand with the least possible spillage, at the same time allowing the proper shock system to develop so that the highest possible total pressure is obtained at the engine face.

To go into these matters in any detail the supersonic power plant designer requires exact knowledge of the performance of the intake over the required range of flight Mach number, engine mass flow and incidence. For present purposes, leaving out the more complex aerodynamic effects, perhaps the easy way of approaching the subject is to consider the intake as having three possible flow regimes, "subcritical," "critical" and "supercritical." These names are given respectively where the flow is less than the choking value, equal to choking with maximum recovery and equal to choking flow but less than maximum pressure recovery. The flow pattern can have the form appropriate to any one regime at each supersonic Mach number of the approaching flow.

In the "subcritical" regime where the flow entering the intake is less than the choking value, some of the air which has passed through the external shock system fails to enter the mouth of the intake and spills over to the outside.

A typical shock system for this regime would be an oblique shock at the apex of the centre body, followed by a secondary but prominent normal shock standing on the surface of the centre body out ahead of the intake lip. The two shocks, oblique and normal, would coalesce at some distance from the apex clear of the intake lip to form a bow wave about the power unit. In this regime the flow behind the secondary normal shock is subsonic and the stream lines bend to suit the shape of the centre body and lip while satisfying the demand of the engine.

If now the ingested flow is to increase with the intake still in the subcritical regime the secondary normal shock must become weaker to allow the Mach number downstream of the shock to rise and so increase the velocity into the intake. The reduced strength, *i.e.* higher downstream Mach number, causes the normal shock to stand closer in towards the lip and at the same time involves less loss of total pressure, which improves the pressure recovery. Mass flow and pressure recovery, therefore, increase together until the point is reached where the secondary normal shock reaches the intake lip and so spans the narrowest section of the flow passage. The intake is then choked and can pass no greater mass flow until the upstream pressure is increased or temperature decreased. This is the "critical" condition separating the subcritical and supercritical regimes.

When pressure recovery and mass flow increase together as they do in subcritical flow, instability is highly probable. It has been a feature of the regime, particularly with ram-jets. Thus if the engine suffers a temporary disturbance from equilibrium which causes a sudden drop in mass flow, the fall in intake pressure fails to restore the flow towards equilibrium and tends to take the flow still further from the steady running point. On the other hand, if the disturbance causes a temporary increase in the flow, pressure recovery rises and thus aggravates the increase. For this reason subcritical operation may be impossible. A lot depends on the presence of other vibrations in the flow, such as disturbances in the combustion chamber of a ram-jet, which may come into resonance and cause very violent fluctuations, known as "buzz," which make it impossible to achieve steady operation. When the turbo-jet engine has a centre body intake there is evidence that intake resonance is less likely because the flow through the turbine has a stabilising effect in the subcritical range, which is a distinct advantage.

Extensive intake investigations have shown that maximum pressure recovery can only be obtained over a narrow range close to the critical condition. Therefore, when the maximum pressure recovery is aimed at it is inevitable that subcritical operation will occur at some points in the flight plan. With the turbo-jet, the spillage on the subsonic side but near to the critical point is probably worth the advantage of maximum pressure recovery, provided the power plant is stable; this is a problem for the specialist in controls. With the ram-jet, where intake instability can lead rapidly to complete failure, it is essential to avoid the subcritical region.

Centre body intakes at high Mach numbers show peaky pressure recovery-mass flow characteristics. For Mach numbers above what one might regard as the limit of the turbo-jet field, about 3 to 3½, the decrease of pressure recovery in the subcritical regime, once the intake unchokes, is rapid. Thus the shock pattern for dealing with high Mach numbers is more complex and appears to be more easily upset by the change from supersonic to subsonic flow about the entry lip. Hence there is an increased tendency towards instability, which adds to the difficulty of operation within the subcritical regime.

These high Mach numbers are the domain of the ram-jet, where the designer is obliged to choose supercritical operation. Here the approach flow stream tube is entirely supersonic and its boundary corresponds with the full intake lip area. The normal shock is swallowed into the intake and its strength is greater than for the critical condition. Since pressure recovery is less than the maximum the intake in effect throttles the engine. The mass flow remains as at the critical condition.

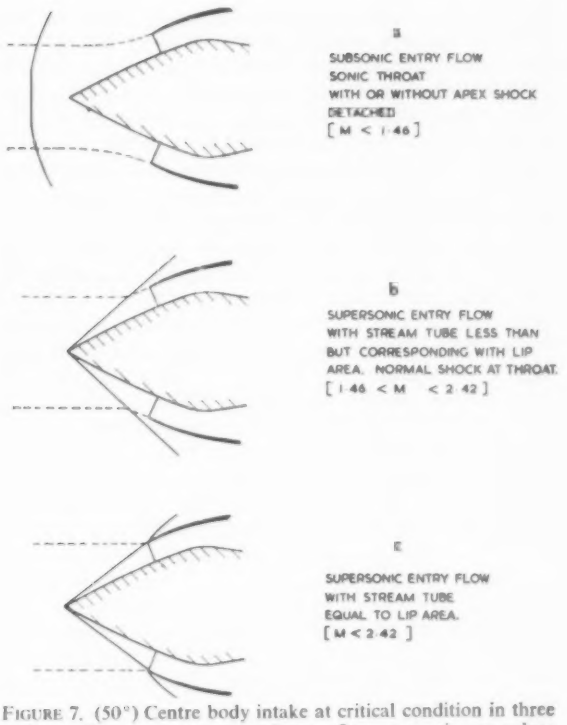


FIGURE 7. (50°) Centre body intake at critical condition in three regimes. Pressure recovery and mass flow at maximum values (lip angle 38°).

Theoretically it is possible for the flow behind the apex shock of a cone to progress smoothly from a supersonic to a subsonic pattern. Thus at low supersonic speeds, intake operation with a conical centre body can be characterised by a region of supersonic flow near the inlet without the appearance of another shock. If the Mach number is further reduced the bow shock separates from the apex and the whole flow about the intake becomes subsonic. The subsonic conical flow and the separated bow wave pattern (where the entry flow is subsonic), will have a common value of choking mass flow parameter $QT^{\frac{1}{2}}/P$, corresponding to sonic flow in the throat which is independent of the flight Mach number. This region of subsonic approach flow can have the three regimes, subcritical, critical or supercritical, according to whether the engine is taking less than the choking flow, is just choking the intake, or has the intake throttled. In all cases of intake operation maximum pressure recovery is obtained at, or just below, the critical mass flow.

To keep close to the critical point, and therefore within the most efficient regime of the intake, over a range of engine mass flows, the throat area must be varied. The centre body may be brought forward to keep the conical shock just ahead of the lip as the bow wave sharpens. This alone will not prevent serious spillage or excessive loss in pressure recovery unless the swallowing capacity of the intake matches that of the engine at each condition.

Air captured by the intake after traversing the normal shock passes through a subsonic diffuser to the engine. The problem of intake/engine matching requires reference to the mass flow parameter $QT^{\frac{1}{2}}/AP$ (or its Mach number equivalent), at the two ends of this subsonic diffuser. For a fixed ratio between the areas of the duct cross section, at the throat and exit of the subsonic diffuser, the corresponding values of $QT^{\frac{1}{2}}/P$ will be in constant ratio, irrespective of the actual mass flow, temperature and pressure, so long as losses are small enough to be neglected. Hence for a fixed geometry, if we know the $QT^{\frac{1}{2}}/P$ at the throat we know it at the engine entry plane and vice versa.

Desirable values of $QT^{\frac{1}{2}}/P$ for the engine are found from its component characteristics. With the turbo-jet, for a given r.p.m., N, and a given flight Mach number which fixes the intake total temperature T, we know the $N/T^{\frac{1}{2}}$ for the compressor, and therefore, the $QT^{\frac{1}{2}}/P$ from the compressor operating line. For the intake we require to establish corresponding values of flight Mach number, pressure recovery and $QT^{\frac{1}{2}}/P$ at the throat for the critical state. We may readily convert the latter to give $QT^{\frac{1}{2}}/P$ at engine entry, and hence the critical intake operating line and desirable engine operating line may be directly compared[7].

Figure 7 shows that the critical intake operating line for a conical centre body intake has three distinct parts where the approach flow is (*a*) subsonic (*b*) supersonic with the conical shock clear of the lip and (*c*) supersonic with the conical shock on or inside the lip. The part (*a*) applies to low supersonic flight speeds where there is a region of subsonic approach flow which includes the detached bow wave regime. Here the critical condition is sonic flow at the intake throat and therefore the $QT^{\frac{1}{2}}/P$ at the engine entry plane is a known constant, and a plot of critical pressure recovery on a base of the latter parameter is simply a vertical line (Fig. 8).

As Mach number increases the second part (*b*) of the critical line is reached. The entire approach flow, at the critical state, is supersonic and a normal shock appears at the throat. The capture stream tube approaching the intake grows slightly larger in diameter as Mach number increases and at all speeds for critical flow is just swallowed with a normal shock of minimum strength. As flight Mach number increases the strength of the normal shock increases, it follows that the subsonic Mach number downstream of the shock decreases. This requires a lower engine entry Mach number. Hence with critical behaviour the engine entry $QT^{\frac{1}{2}}/P$ falls as flight Mach number increases. The critical pressure recovery also falls because of the increased losses with the stronger normal shock. This part of the critical curve is, therefore, one of decreasing $QT^{\frac{1}{2}}/P$ at engine entry and decreasing pressure recovery.

On a further increase of Mach number, the conical shock makes contact with the intake lip and may partly enter the intake passage. The steady increase in mass flow Q which occurred in (*b*) as the capture stream tube grew, now ceases, but the normal shock continues to strengthen. Part (*c*) of the critical curve is thus characterised by an increased rate of reduction of engine $QT^{\frac{1}{2}}/P$ with Mach number.

The critical curve of Fig. 8 just described gives the

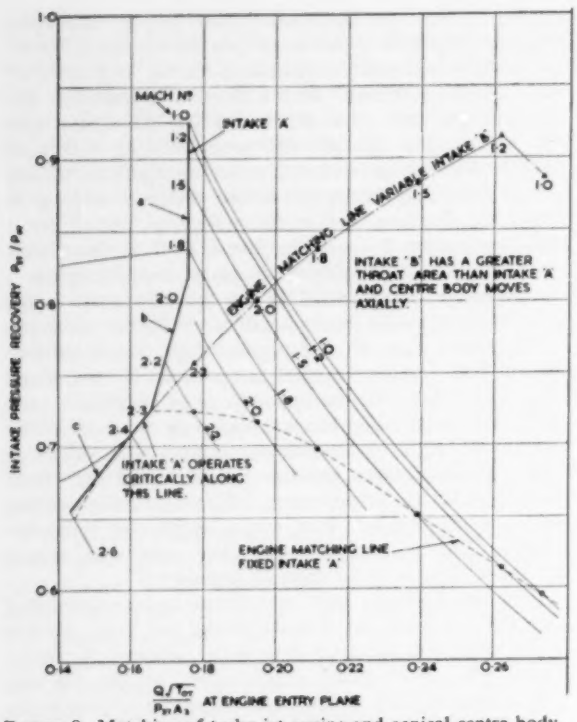

MACH NO
INTAKE 'A'
VARIABLE INTAKE 'B'
MATCHING LINE
INTAKE 'B' HAS A GREATER THROAT AREA THAN INTAKE 'A' AND CENTRE BODY MOVES AXIALLY
INTAKE 'A' OPERATES CRITICALLY ALONG THIS LINE
ENGINE MATCHING LINE FIXED INTAKE 'A'
INTAKE PRESSURE RECOVERY
AT ENGINE ENTRY PLANE

FIGURE 8. Matching of turbo-jet engine and conical centre body intakes. Stratosphere. Constant engine r.p.m.

pressure recovery at the minimum mass flow for the given Mach number on a base of engine entry $QT^{\frac{1}{2}}/P$. The area to the left of the curve is for subcritical operation and the right hand region is the supercritical.

The supercritical region in effect is where the engine demand exceeds the intake supply and so the engine is throttled, receiving its supply at a diminished pressure. In aerodynamic language this is brought about by a strengthening of the shock near the throat of the intake passage. For a given flight Mach number, in supercritical operation the engine inlet $QT^{\frac{1}{2}}/P$ is inversely proportional to the pressure recovery, the constant of proportionality decreasing with Mach number. Hence a curve of constant Mach number for the supercritical region is a rectangular hyperbola which approaches the two axes more closely as the flight speed goes up.

A turbo-jet engine in supersonic flight at constant r.p.m. suffers an increasing intake temperature, and therefore a decreasing $N/T^{\frac{1}{2}}$, as Mach number rises. Hence if the engine is to remain on a normal operating line, as indicated by the matching line with a variable intake "B," or with the fixed intake "A," the $QT^{\frac{1}{2}}/P$ at the engine entry plane must fall. This fall will follow to some extent the fall in $QT^{\frac{1}{2}}/P$ of the critical intake curve. (Part "*c*" (Fig. 8)). However if the intake is made big in order to be a better fit in the subsonic approach regime it can be inferred from a plot like Fig. 8 how far a Mach number increase will send it into subcritical operation. On the other hand, if the intake throat is dimensioned to suit the parts of the critical curve for supersonic approach flow, it will be too small for subsonic approach flow and cause severe loss of pressure recovery in that regime. The idea is to keep the throat area adjusted so that the engine point is close to the critical curve. To do this, we must either close the intake down progressively as the $QT^{\frac{1}{2}}/P$ requirement of the engine falls with increasing flight speed or attempt to regulate the engine in another way.

If the turbo-jet is regulated to run at constant $N/T^{\frac{1}{2}}$ instead of constant N, in which case its r.p.m. will rise progressively with Mach number, the engine entry $QT^{\frac{1}{2}}/P$ will be constant, which will permit exact matching with the intake critical curve in the subsonic approach regime ("*a*" Fig. 8). However as soon as the flight speed allows fully supersonic approach flow, some pressure recovery is lost by maintaining constant $N/T^{\frac{1}{2}}$. The required decrease in engine $QT^{\frac{1}{2}}/P$ to give maximum pressure recovery at the highest speeds ("*c*" Fig. 8) is much more in keeping with constant r.p.m. regulation. For the intermediate region, where the approach flow is supersonic and the entry stream tube is still growing, a control somewhere between constant $N/T^{\frac{1}{2}}$ and constant N is desirable.

If variable geometry of intake is introduced along with variable N control for supersonic turbo-jets, both intake and engine will require less alteration with increase in forward speed. This illustrates how the intake and engine combination must be, more than ever, one and the same design.

4. Thrust Minus Drag

Ideally the air intake should supply the engine demand at the highest pressure recovery with the minimum of external drag. Unfortunately these two properties are inter-related and cannot be optimised simultaneously. Thus a fixed centre body intake cannot give its peak pressure recovery over a Mach number range without some spillage drag, and then only at definite mass flows which are not likely to suit the engine except in a narrow thrust range. Again an intake improvement giving an increase in critical pressure recovery will be associated with a fall in $QT^{\frac{1}{2}}/P$ at the engine entry plane. With a turbo-jet a fall in $QT^{\frac{1}{2}}/P$ implies a drop in r.p.m., turbine inlet temperature and therefore thrust, so that it is possible for an apparent improvement in intake efficiency to result in a loss in engine output.

Thus, it is necessary to consider the thrust-minus-drag of the propulsive system as the objective rather than the simple thrust; and with sufficient intake and engine data available, the problem, in its early stages at any rate, is primarily one of choosing the best intake matching point.

In the evaluation of a new design from the thrust-minus-drag aspect, one would expect to start with an existing engine-intake combination and to bring to bear new knowledge of the effects of proposed improvements on the thrust and the drag. The most satisfactory balance of the thrust-minus-drag relation can only be discovered by flight development, for, quite apart from engine and intake performance it depends on the thrust-speed characteristic of the aircraft. The

optimisation will, therefore, depend on any changes in aircraft drag brought about by changes in component weights and engine fuel consumption[8].

Let us assume for discussion that we have a turbo-jet and intake already selected and that matching at a particular Mach number will occur in the supercritical region. Let us assume that we can increase the pressure recovery in steps to the critical point, then since the pressure at the engine entry plane increases, while the mass flow and total temperature remain constant, the corresponding $QT^{\frac{1}{2}}/P$ decreases. The r.p.m. and turbine inlet temperature then fall and hence, despite the increased intake pressure, the engine thrust falls. Meanwhile, the external air flow does not alter and so the intake drag remains constant. We thus deduce that the thrust-minus-drag of the combination must fall as the pressure recovery rises. In the supercritical regime, therefore, the thrust-minus-drag is highest at the lowest pressure recovery where the r.p.m. and turbine inlet temperature are highest. This point where the accepted engine limitations are reached would be regarded as the matching point of the combination.

Since the thrust of a turbo-jet at constant r.p.m. and Mach number always increases with compressor air entry pressure, it would improve both thrust and thrust-minus-drag if the combination could be matched at the point of maximum pressure recovery. There would then be no possibility of keeping within the desirable stability of the supercritical regime except by over-speeding the engine.

Next let us suppose that matching at our particular Mach number will occur in the subcritical regime. The point of maximum thrust-minus-drag may now be found if we take downward steps in mass flow decreasing from the critical. These steps correspond to increased spillage from point to point. Over this range the pressure recovery is likely to rise slightly and then fall slightly as spillage increases. The engine entry flow parameter $QT^{\frac{1}{2}}/P$ is now governed principally by the changes in Q and will decrease progressively. It follows that r.p.m., turbine inlet temperature and thrust must fall.

At the same time the intake drag will rise because more of the air, partly compressed by intake shock waves, is spilled. We can imagine an annulus of increasing thickness shaved off the approaching stream tube before it enters the intake and being wasted overboard. The drag force is due to the static pressure generated in the shock waves through which the annulus passes. The cross sectional area of the annulus varies linearly with the spillage; the intake drag therefore rises linearly.

Since a decrease in engine thrust and increase in intake drag occur as the spillage increases in the subcritical regime, it is concluded that thrust-minus-drag continues to fall as the engine passes from supercritical through the critical to subcritical intake operation.

A more or less sharp discontinuity in the thrust-r.p.m. curve of the turbo-jet occurs at the critical intake point (Fig. 9). When the engine is brought from the supercritical into the subcritical intake regime by

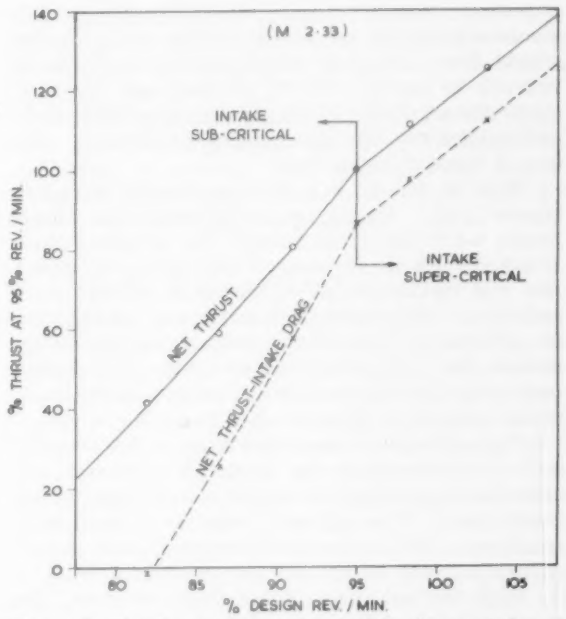


FIGURE 9. Net thrust and net thrust-intake drag variation at constant Mach number.

reducing the fuel flow, an increase in engine entry pressure occurs. This ceases at the critical point but is followed immediately by a decrease in engine mass flow. As far as the fall in the value of $QT^{\frac{1}{2}}/P$ is concerned it is immaterial whether P increases or Q decreases, and so the r.p.m., which is determined by $QT^{\frac{1}{2}}/P$, changes smoothly if the operating point is brought steadily through the critical point. However, the engine thrust falls more rapidly with the decrease of Q than with the increase of P. This is because the falling r.p.m. is the prime cause of the thrust reduction but is resisted in the supercritical regime by the rising intake pressure which tends to recover thrust. At the critical point the pressure effect ceases as the mass flow begins to fall, and so a downward kink is produced in the thrust-r.p.m. curve. One would expect this discontinuity to be a feature of the handling of the supersonic turbo-jet if operated through the critical regime.

If the increasing drag of the subsonic regime is subtracted from the decreasing thrust, it is seen (Fig. 9) that the discontinuity in thrust-minus-drag at the critical point is even sharper than for the thrust alone.

One way of avoiding a discontinuous thrust curve at any given Mach number would be to operate always subcritically or supercritically. With a turbo-jet, to achieve maximum thrust it would be advantageous to operate subcritically all the time. The intake would have to be designed so that the maximum $QT^{\frac{1}{2}}/P$ at the engine entry is reached just short of the intake critical flow. The engine thrust at each r.p.m. would then be close to the maximum available for the particular flight condition. Spillage drag would occur over the full r.p.m. range but would decrease towards the upper extreme where maximum thrust-minus-drag is most

important. A main problem, particularly at high Mach numbers would be the stability of the intake in subcritical flow. At lower Mach numbers it would be desirable to employ variable geometry and widen the intake throat, or the intake will operate supercritically and re-introduce the discontinuous thrust curve, with loss of thrust at higher r.p.m.

With the ram-jet it is more convenient to operate supercritically. During the boost phase of a ram-jet missile the intake passes through the subcritical phase. It should reach the supercritical state before the separation and remain in this regime which ensures stable behaviour. Maximum thrust-minus-drag of the ram-jet calls for a nearly constant fuel/air ratio and for the intakes that have been proposed a constant fuel/air ratio sends the intake more and more into the supercritical regime as Mach number rises.

Figure 10 shows some estimates of engine net thrust and thrust-minus-drag for a straight turbo-jet with orthodox constant r.p.m. control and a conical centre body intake. Two curves *A* refer to a fixed intake matching at $M=2{\cdot}3$ and two others *B* to a variable geometry intake suitable for speeds up to $M=2{\cdot}3$.

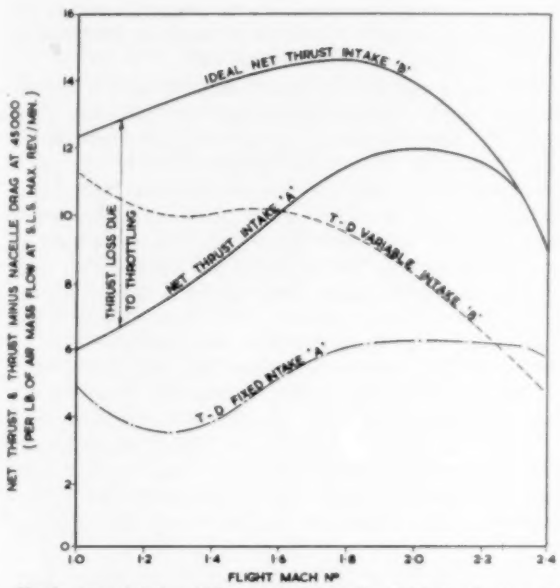
With the fixed intake, loss of thrust occurs at Mach numbers below 2·3 because the intake flow is supercritical. This means that the engine loses intake pressure as well as air flow by being throttled. The drag term takes into account the usual drag loads on nacelle and afterbody; it also includes a term for the difference in momentum of the stream tube between infinity up-stream of the engine and the intake entry plane, because the net thrust is based on the stream tube condition at infinity. There is no spillage drag.

If the intake is made variable over the Mach number range, then in theory it can provide full pressure recovery and all the mass flow required by the engine. Allowance is made in Fig. 10 for the variable intake to be of slightly larger diameter than the fixed intake because it must have a wider throat at lower speeds. Also, there is a small spillage loss because the supercritical regime is avoided by a small margin.

At the cruising Mach number of 2·2 to 2·3, the thrust-minus-drag of both systems is the same, but in the region of $M=1$ the variable intake gives more than double the thrust-minus stage of the fixed intake. This example serves to show the importance and the scope for correct intake design.

5. Combustion

The development of the air-breathing engine for supersonic flight demands much research to widen the operating field of the combustion system. The success of the turbo-jet and ram-jet will depend largely on the potentialities of the combustion process. We are not only concerned with improving the known techniques of the turbo-jet combustor. It is also necessary to develop burners for near stoichiometric mixtures in order to obtain the maximum possible heat release. The highest mass flow rates, with velocities approaching sonic, and the limiting flame temperatures of which combustion of fuel is capable, are required in the reheat pipe and in



Single cone intakes 30° apex semi-angle. "A" fixed geometry matched at $M=2{\cdot}3$. "B" variable geometry. Throat area and cowl diameter greater than "A". Engine r.p.m. constant.

FIGURE 10. Net thrust and net thrust minus nacelle drag of turbo-jet with conical centre body intakes.

the ram-jet. Success will depend largely on overcoming the high temperature problems in the burner chamber itself. In the development of a suitable system the following are likely to be the main considerations.

An acceptable order of pressure loss must be maintained through the burner in spite of the modifications which are made to obtain increased ability in other directions and which generally tend to increase such loss.

The burner must burn all the fuel as efficiently as possible and have wide extinction limits to cope with possible transients in the engine air flow. For example, under many flight conditions a ram-jet may be made to operate successfully, yet it may be impossible to relight the engine if extinction occurs.

A reduction of the combustion chamber size will show considerable benefits in weight saving. For a high efficiency it is necessary to contain the combustion within the engine envelope. This can only be done with very rapid burning and mixing. More efficient mixing devices and improvements in fuel injection must not increase the aerodynamic pressure loss.

The pressure received by the reheat or ram-jet burner has an effect on the permissible intensity of combustion and the rate of reaction in the combustion process. Pressures above one atmosphere present no difficulties, except that high pressures tend to cause over-heating of flame stabilisers and other burner parts due to proximity of the flame. Sub-atmospheric pressures present increasing difficulties. There is a limiting pressure below which combustion in a ram-jet type of burner cannot be sustained.

Future applications of the ram-jet may well

necessitate burner operation within wide limts of air inlet temperature, say 0°C to 500°C. High inlet temperatures are likely to present problems mainly concerned with mechanical reliability whereas low temperatures—less than 100°C—reveal problems of a more fundamental nature concerning the fuel supply to the burner. Vaporisation of the fuel after injection and before burning is an important part of the combustion process. In the ram-jet, if the inlet air temperature approaches 0°C this vaporisation stage is non-existent. The ability of a fuel injector to provide finely atomised droplets under such conditions is likely to be strictly limited by practical restrictions on fuel supply pressure. For the ram-jet it is then necessary to turn to more volatile fuels than the normal kerosine used, *i.e.* "wide cut," or petrol. More exotic fuels may need to be considered in the 0°C region in an attempt to get more rapid burning of the droplets. One other possible solution to this problem is to use a self-vaporising fuel system which extracts its heat from the flame, but this probably requires a special fuel for starting the burner.

One of the attributes of the supersonic ram-jet is its high thrust per unit frontal area. As frontal area is controlled by combustion chamber area a higher thrust/ft.^{2} can be achieved by allowing increased velocities in the combustion zone. Progress in this respect is of necessity very gradual, for burner performance is very sensitive to velocity increase and to any reduction in residence time.

The mechanical reliability of the combustion system of the air breathing engine depends on cooling air for preserving the structure. An obvious line of development is to try to reduce the amount of air which bypasses the burner for this purpose.

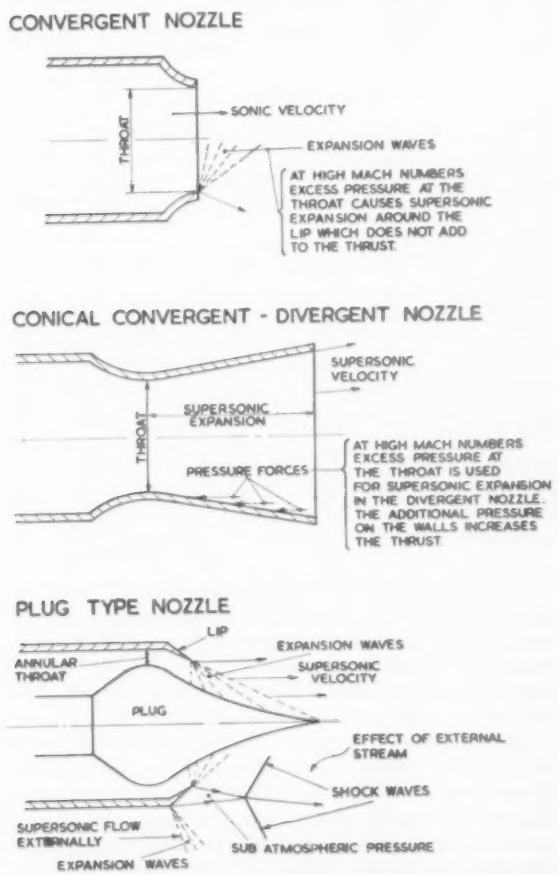

CONVERGENT NOZZLE
THROAT
SONIC VELOCITY
EXPANSION WAVES
AT HIGH MACH NUMBERS EXCESS PRESSURE AT THE THROAT CAUSES SUPERSONIC EXPANSION AROUND THE LIP WHICH DOES NOT ADD TO THE THRUST
CONICAL CONVERGENT - DIVERGENT NOZZLE
THROAT
SUPERSONIC VELOCITY
SUPERSONIC EXPANSION
PRESSURE FORCES
AT HIGH MACH NUMBERS EXCESS PRESSURE AT THE THROAT IS USED FOR SUPERSONIC EXPANSION IN THE DIVERGENT NOZZLE. THE ADDITIONAL PRESSURE ON THE WALLS INCREASES THE THRUST
PLUG TYPE NOZZLE
LIP
ANNULAR THROAT
EXPANSION WAVES
SUPERSONIC VELOCITY
PLUG
EFFECT OF EXTERNAL STREAM
SHOCK WAVES
SUPERSONIC FLOW EXTERNALLY
EXPANSION WAVES
SUB ATMOSPHERIC PRESSURE

FIGURE 11. Convergent nozzle, conical convergent-divergent nozzle and plug type nozzle.

6. The Final Propelling Nozzle

Provided that the overall pressure ratio of the final nozzle between its inlet plane and the atmosphere does not exceed about 1·85, the exhaust gas stream accelerates subsonically and can therefore be contained within a converging duct. This type of nozzle has its effective throat at the exit plane and its construction is simple enough to permit exit area variation for reheat.

In supersonic flight overall nozzle pressure ratios are likely to be of the order of 10 or 15 to one which is well above the critical of 1·85. If such a nozzle is made a simple convergent one, the excess pressure after the throat will be dissipated in expansions round the exit lip. Such an expansion cannot add sensibly to the thrust because the excess pressure in the external jet does not act on any part of the engine structure (Fig. 11).

The convergent-divergent fixed geometry nozzle is common practice in rocketry where very high overall pressure ratios are currently employed. The same principle of a converging-diverging passage will be necessary for the supersonic air breathing engine. With a nozzle which is only convergent, even at a Mach number of 1·5, 10 per cent of the available thrust is lost; at a Mach number of 3 the loss would be 50 per cent. Clearly such losses would detract greatly from the possibility of economic supersonic flight. The principle of the convergent-divergent final nozzle must, therefore, be adopted when the overall pressure ratio exceeds 1·85 by a certain margin which will reflect the cost in mechanical complexity, extra weight, and any loss in off-design performance compared with a plain convergent pipe. The divergence may be on the outer wall which gives the nozzle the familiar rocket motor shape or on the inner wall, as in the plug type nozzle (Fig. 11). The gas pressures on the divergent wall give an axial resultant force and this is the thrust that would be lost by a simple convergent nozzle.

Base drag arises if the air pressures outside the rear of the nacelle, on the annulus between the jet cross section and the nacelle base circumference, fall below atmospheric. The ratio of the areas of the nozzle passage between throat and exit is the design variable controlling the area of this annulus. If this area ratio is 2, which is about correct for an overall nozzle pressure ratio of 10 to one, the final exit diameter with outer wall divergence will be roughly the same as the engine outside diameter (Fig. 12). In this case the base drag annulus area is very small.

With the plug type nozzle there is an annulus susceptible to base drag. Also, the low base pressures,

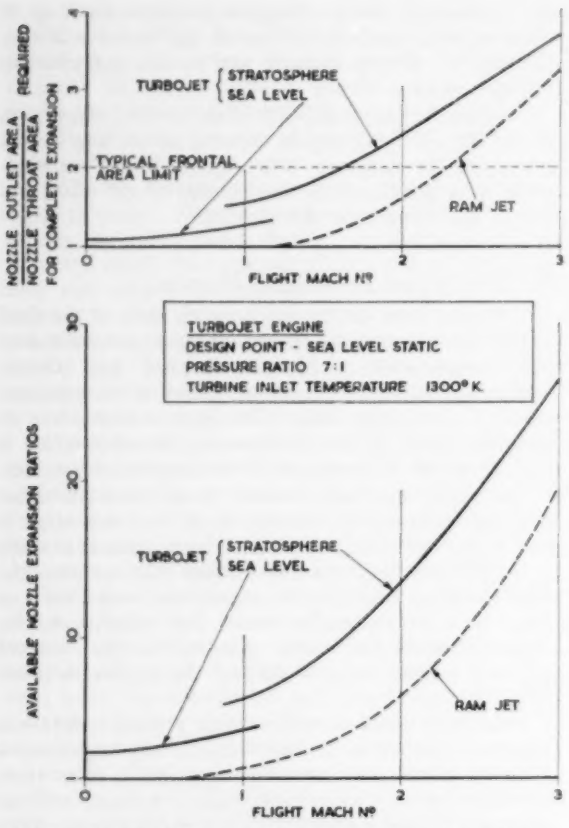

NOZZLE OUTLET AREA / NOZZLE THROAT AREA FOR COMPLETE EXPANSION
TURBOJET { STRATOSPHERE / SEA LEVEL
TYPICAL FRONTAL AREA LIMIT
RAM JET
FLIGHT MACH Nº
TURBOJET ENGINE
DESIGN POINT - SEA LEVEL STATIC
PRESSURE RATIO 7:1
TURBINE INLET TEMPERATURE 1300° K.
AVAILABLE NOZZLE EXPANSION RATIOS
TURBOJET { STRATOSPHERE / SEA LEVEL
RAM JET
FLIGHT MACH Nº

FIGURE 12. Propelling nozzle areas and expansion ratios.

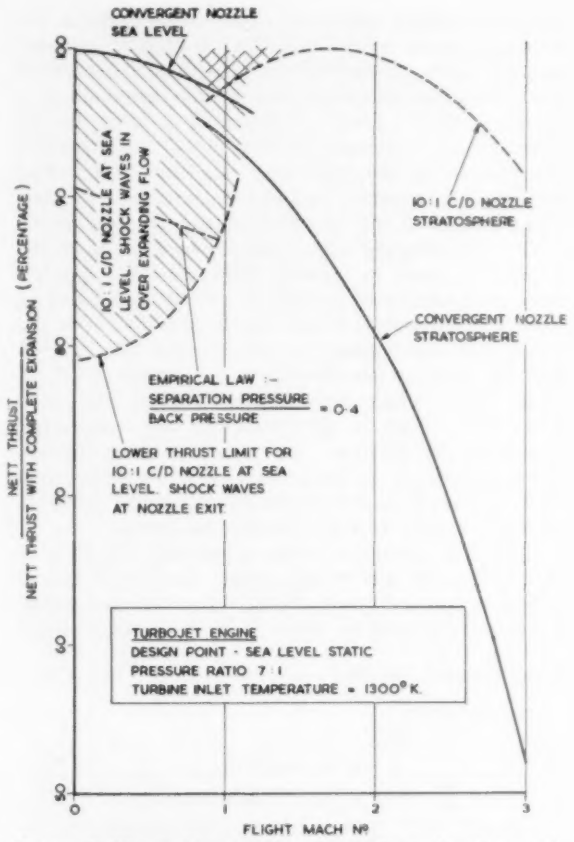

CONVERGENT NOZZLE SEA LEVEL
10:1 C/D NOZZLE AT SEA LEVEL SHOCK WAVES IN OVER EXPANDING FLOW
10:1 C/D NOZZLE STRATOSPHERE
CONVERGENT NOZZLE STRATOSPHERE
EMPIRICAL LAW :- SEPARATION PRESSURE / BACK PRESSURE = 0·4
LOWER THRUST LIMIT FOR 10:1 C/D NOZZLE AT SEA LEVEL. SHOCK WAVES AT NOZZLE EXIT
TURBOJET ENGINE
DESIGN POINT - SEA LEVEL STATIC
PRESSURE RATIO 7:1
TURBINE INLET TEMPERATURE = 1300° K.
NETT THRUST / NETT THRUST WITH COMPLETE EXPANSION (PERCENTAGE)
FLIGHT MACH Nº

FIGURE 13. Thrust characteristics of turbo-jet engine plus nozzle.

which cause the drag, tend to make the jet over-expand on the plug surface (Fig. 11). These sources of thrust loss must be minimised by careful shaping of the nacelle afterbody and the plug surface. The plug appears to be the simplest way of constructing a convergent-divergent nozzle with a variable throat area.

Figures 12 and 13 show some estimates of available nozzle expansion ratio and area ratios, together with the thrusts for a propelling nozzle fitted to a turbo-jet engine. The engine pressure ratio is seven to one (at sea level static) and a constant engine r.p.m. is assumed between a Mach number of zero and $M=3$ in the stratosphere. The convergent-divergent nozzle used for Fig. 13 is assumed designed to suit a ten to one nozzle expansion ratio and the thrust comparison is on a percentage basis, with 100 per cent referring to the thrust ideally obtainable with complete adiabatic expansion.

It is seen from Fig. 13 that with the 10:1 convergent-divergent nozzle, performance begins to be significantly superior to the plain convergent nozzle above about $M=1{\cdot}5$. At $M=3$ the 10:1 nozzle develops about 90 per cent of the thrust attainable with complete expansion to ambient pressure, compared with 50 per cent developed by the convergent nozzle. The last 10 per cent of the ideal thrust could only be achieved by making the nozze exit area greater than the maximum engine diameter, and this would decrease the overall thrust-minus-drag.

There is a difficulty in trying to predict the thrust of the convergent-divergent nozzle for subsonic speeds, because the pressure ratio available is less than the design pressure ratio of the nozzle. The nozzle will either over-expand the jet or require separation of the flow from the walls in the divergent part of the passage. For an outwardly diverging nozzle, one experimental rule states that separation will occur at a plane where the local pressure falls below 40 per cent of the (atmospheric) outlet pressure. Assuming this rule applies, a 10 to 15 per cent thrust loss will occur in subsonic flight, for the engine specified. The sea level static loss could be as high as 20 per cent of the full thrust if the flow did not break away, for then the jet would suffer the maximum of over-expansion. From this point of view the ideal form of nozzle would have to change from a convergent-divergent form to the simple convergent form for the take-off and subsonic flight. To some extent this can be done aero-dynamically by allowing outside air into the nozzle to fill the convergent path, while the low pressure gas which would otherwise separate from the walls assists the inflow by ejector action.

Figure 14 attempts to shed more light on the problem of over-expansion by presenting curves of

local pressure plotted against flow path area. Thrust calculations usually assume the ideal state with over-expansion to be isentropic expansion to a local pressure which is less than atmospheric, followed by a normal shock and subsonic diffusion rising to the atmospheric pressure at exit. Experiments show that in actual fact the initial expansion to sub-atmospheric pressure is ended by an oblique shock and then separation of the flow from the walls occurs with a slight rise in pressure to the exit.

The curves give theoretical relationships connecting local pressure and flow area for normal shock or oblique shock where the pressure rises from the isentropic condition. The loci plotted show the pressure-area variation during subsonic diffusion after a normal shock, and the pressures reached after an oblique shock corresponding to a constant two-dimensional wedge angle. From the work of Ashwood[9] the area within *AAA* in Fig. 14 corresponds to the region of unstable flow. Below *BBB* the flow is definitely stable. Between these two boundaries it is not possible to say what particular régime will form.

Summerfield shows[10] that the breakaway point with rocket gases ($\gamma = 1{\cdot}22 - 1{\cdot}26$) corresponds to a constant wedge angle of about 13° which is independent of the divergence angle. A constant wedge angle of 13° for $\gamma = 1{\cdot}4$ would give the locus *CC*.

7. Some Other Considerations

In addition to the novel problems of intake, combustion and final nozzle an air-breathing supersonic engine requires the following features to be developed to the highest possible standard.

(*i*) High thrust at cruise; which implies proper integration with the intake and afterbody or wing design, as well as suitable performance characteristics, including the minimum sensitivity to high air intake temperatures.
(*ii*) Low weight as a fully installed power plant.
(*iii*) Low cruising fuel (and oil) consumption.
(*iv*) Reliability and good overhaul life for the engine and all engine-driven accessories.
(*v*) Simplicity and ease of maintenance.
(*vi*) Ample safety margin should any forseeable failure occur in flight.
(*vii*) Low noise level.

These factors are in fact demanded of any aero-engine. They are so complex that the best compromise can only be obtained by experience. Yet the success of the supersonic engine will depend on the emphasis being placed on them in the correct way at the start, for it will not be possible to get a vast experience in this field for a long time.

For example, take a civil aircraft to cruise in the region $M = 1{\cdot}5$ to $M = 2{\cdot}0$, say with turbo-jet aircraft. The engines should be conservatively designed to give more reserve power, greater safety, reduced overhaul costs and freedom from breakdowns. At first sight this can most readily be done by designing for a relatively low gas temperature and accepting a lower specific

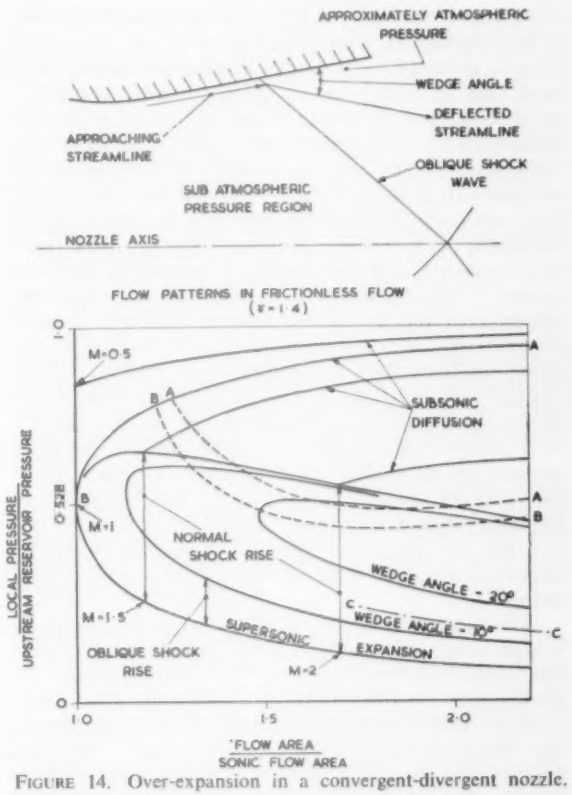


FIGURE 14. Over-expansion in a convergent-divergent nozzle.

thrust. This will also give a better subsonic fuel consumption, which is important for reserve allowances. According to calculations, however, the low temperature turbo-jet is adversely effective both in altitude thrust and fuel consumption at high Mach numbers. Further, the designer must provide adequate protection for the engine from debris, fire and icing as well as offering a noise suppressor, and thrust reverser for landing. These are bulky items which can penalise the large low-temperature engine rather severely partly on account of their weight, and partly due to the sensitivity of the low temperature engine to intake and exhaust pressure losses. Hence one is forced to reconsider higher operating temperatures with their involved cooling problems, more costly construction and reduced life, and try to decide whether the regression in reliability, higher subsonic fuel consumption, and higher first cost will be worth the gain in thrust and reduced penalties of the auxiliary equipment.

Again, when studying the question of the best size of turbo-jet, the designer is very concerned with the weight of the engine and the way it is influenced by the square-cube law. This law applies rigidly to similar engines above a certain size where lengths and diameters are held in proportion. Thus for turbo-jets it is clear that best specific weights will not be obtained with engines of large size. Nevertheless, the influence of previous experience in manufacture and development, and desire for progress, usually tends towards larger engines.

In theory, specific weight of the turbo-jet diminishes as size diminishes down to a point where the power plant would become a multiplicity of small units. Each small unit of such a power plant must be accurately speed-controlled to prevent any failure of its highly stressed parts. The control unit itself is not amenable to the square-cube rule and so becomes more and more noticeable as a fraction of total engine size and weight. With subsonic aircraft, we are still in the stage of increasing unit thrusts because aircraft sizes continue to go up, and four engines is still about the right number. With supersonic aircraft although required thrusts are high by present standards, there is more resistance against engine weight that can be avoided by proper design. But no aircraft man likes too many engines and we have yet to see how far design will progress in favour of a multiplicity of smaller units.

Turning to the attractions of the ram-jet engine, a primary consideration is to what extent engine and airframe can be combined as one unit. For example, can the outer shell of the engine be utilised as wing surface and how far can the air flow into the intake permit an increased depth of wing in the interests of structural strength?

The good performance of the ram-jet will depend on a high intake efficiency, which can only be obtained if the intake operates close to the critical regime. A leading problem is how near to critical condition is best with the peaky intake pressure-recovery characteristics one associates with high Mach numbers. Variable intake and exhaust geometry will be essential to widen the speed range of the engine. Some variation of pressure recovery in the supercritical regime will be needed for thrust control, in which case a margin of pressure recovery must be allowed. This requirement implies a reduced design efficiency which tends to force up the operating temperature of the engine.

A further difficult problem with the ram-jet is the provision for sufficient take-off thrust and transonic thrust. Unless a satisfactory solution is offered the ram-jet will always be limited to the missile field.

With regard to the other possible forms of supersonic air breathers, little is known apart from a few more or less inspired guesses of probable performances. Whether the turbo-rocket or the re-heated by-pass engine will be the best compromise between ram-jet and turbo-jet can only be proved by future work. Whether the contra-rotating compressor engine or the ejector turbine engine will be developed is even more problematical since these units are so restricted in scope as to make their special advantages quite dubious at the present time.

8. Conclusion

These notes mention only some aspects of supersonic engine design and the forms the air breather can take. The leading feature of the air-cycle aero-engine, *i.e.* ample ram compression, forces early interest upon the intake and exhaust arrangements. Some elementary considerations of these components have been given. Work in the field of combustion is going forward and we can expect this branch of technology to advance with requirements. A very pertinent inquiry in connection with the subject is, of course, the question of the future importance of supersonic aircraft. No hard-pressed engineering organisation will seek to solve so many problems without serious incentive.

ACKNOWLEDGMENT

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The Bloodhound*

by

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1. Introduction

A surface-to-air guided weapon system is the result of many years work by a large and diverse team and includes radars and fire control equipment as well as the actual missile. In the time available it is impossible to cover the whole weapon system and therefore no apology is made for concentrating on the development history of the missile itself. It must be remembered, however, that there are many parts of the Bloodhound weapon system, a major contribution to the whole, which will not be mentioned.

The Bloodhound missile is the result of collaboration between teams at the Bristol Aeroplane Company and Ferranti Limited. It was decided that from the beginning this should be a partnership, with neither team subordinate to the other. This relationship has done much to avoid too little attention being given to particular aspects of the development. This has necessarily called for much self-restraint on both sides, which can be based only on years of mutual respect.

2. Historical

2.1. TERMS OF REFERENCE

Since any major project requires many years of development to come to fruition, its success depends a great deal upon the correct anticipation of the operational need: well engineered projects have in the past come to grief because of a lack of this. When we entered the field, surface-to-air missiles were at that time under way for both the Navy and the Army.

The first stage was to set up a working party to study the techniques by which the objective should be achieved. The working party had available to it the expert advice of many Government establishments, and it recommended the following techniques.

2.2. GUIDANCE

The general considerations taken into account were the need for high fire power and the use of tracking radars which did not impose major radar development problems. For reasons of ability to achieve long range the guidance system had to permit much of the missile flight to be at high altitudes, and for accuracy of interception at long range the use of homing was essential.

All these requirements were met by the use of semi-active homing from launch. In this system, the target is illuminated by a ground radar while a receiver in the missile is locked on to the reflected signal from the target. The missile is not then constrained to follow a line of sight trajectory, and the fire power is not limited by the number of radars available.

2.3. PROPULSION

The use of rocket, ram-jet or turbo-jet was considered. The ram-jet was competitive with the rocket at short ranges and gave great range development potential because of its lower propellant consumption. The expendable turbo-jet engine was not competitive at any range.

The choice of ram-jet propulsion was therefore made on grounds of performance, although not without some misgivings from the point of view of development time since supersonic ram-jet propulsion had not then been achieved in this country.

2.4. TECHNIQUES TEST VEHICLES

No attempt was made to design a weapon system at once and attention was concentrated on building up the engineering team and establishing the techniques of guidance and propulsion. Two test vehicles, initiated by the Royal Aircraft Establishment and subsequently developed by the firms, enabled this to be done. Firings of both types of test vehicle began less than six months after the decision on choice of guidance and propulsion had been made.

2.4.1. *C.T.V.4*

This missile was used by Ferranti for guidance, control and parachute recovery development. It was a coasting dart, boosted and carrying a homing receiver and controlled through the medium of an actuator block with cruciform control fins (Figs. 1 and 2).

Apart from one or two samples from the U.S.A. no sub-miniature valves were available and the early development work was done with ordinary miniatures.

Later a supply of valves began to arrive and a fairly successful C.T.V.4 was fired which contained receiver elements. Two similar rounds were fired with the automic frequency control loop closed, and these seemed to function reasonably. (The presentation of early telemetry sets was not very convincing.) These tests since each missile contained quite complex circuits, encouraged the construction of a round which included a complete target echo receiver.

This round used about 60 sub-miniature valves (three times the number in previous rounds) and gave considerable trouble during preparation, little of which could be blamed on the valves used. It was fired on its fourth visit to the Larkhill range and was satisfactory.

After these firings everything went wrong. Seven rounds were fired, five being complete and two containing partial receivers.

*The fifth lecture to be given to the Guided Flight Section of the Society—on 27th October 1958.

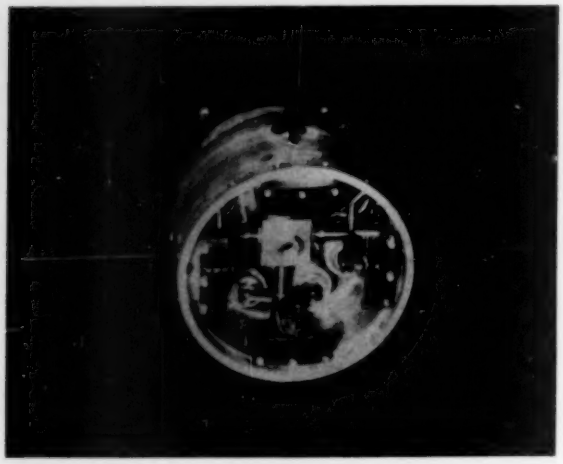

FIGURE 1. C.T.V.4 actuator block.

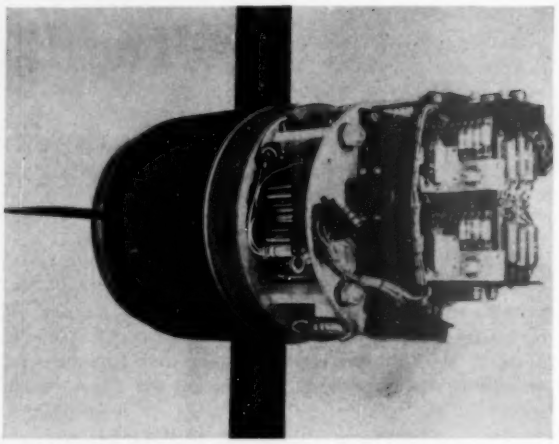

FIGURE 2. C.T.V.4 block with amplifiers.

It is perhaps worth emphasising the difficulty of fault-finding in a complex assembly of circuits when the only available information is 20 low-frequency records of waveforms at places chosen *before the failure*.

So little information was gleaned from these unsuccessful firings that the signal strength became suspect and two simple receiver rounds were constructed with the idea of making a series of exhaustive ground measurements, followed by firing under closely controlled conditions.

It is worth digressing to explain that until this time only odd tests had been made on the sub-miniature valves provided. Each box was usually inspected for cracked bases (2-4 per cent) which seemed a common fault, and the occasional open circuit heater was noted: one specimen suffered from a leaky lead wire.

During the tests on the two rounds it was noticed that any impact on the missile body caused a momentary failure of the circuits and this was rapidly traced to the valves. Furthermore, some valves when tapped directly failed completely and showed the tiny glowing filament normally caused by organic fibres carbonised during pumping, and named lint for convenience. Very often the supply voltages burnt out the filament and on an oscilloscope the anode voltage bottomed for a number of milli-seconds.

The critical places were inter-grid (which glowed) and grid-cathode (which did not), and at this particular time the valves supplied were more than 50 per cent affected. Some, in fact, gave a rather pretty "Christmas Tree" effect during the first few taps, and the trouble was so obvious that normal microphony took second place.

In order to prove that this effect was the cause of our failures, the two rounds were immediately re-valved with tap-tested specimens, all valves were rubber mounted and the missiles were shock-tested at frequent intervals during preparation. (During the early weeks this was done by hammers, replaced as soon as possible by a lead block drop test.)

The first missile fired worked perfectly, while in the second we were fortunate enough to develop an intermittent short-circuit effect in a valve with a telemetry point on its anode. This showed precisely the waveforms that a "lint" fault in the valve caused in the laboratory, and seemed to be most serious at speeds only a little above $M = 1$, where buffeting might be intense.

Two complete receiver rounds were constructed, using the same valve selection procedure, and in both cases all circuits worked during flight (a launching fault upset the strobe unit of the second, but it later tracked an echo correctly). Crude though all this work may seem by present standards, it did establish that our trouble lay in the sub-miniature valves, and that it was possible to select samples which gave any particular missile a good chance of success.

These techniques led to those which are now the basis of Bloodhound reliability.

2.4.2. *J.T.V.*1.

This missile (Fig. 3) was used by Bristol for ram-jet work. It carried two six inch diameter ram-jets on a slender body which contained the fuel and fuel flow controls, and was the most difficult possible missile for an airframe designer to cut his teeth on. At one time it was called "the only fully separating test vehicle" in view of its tendency to fly to pieces, usually towards the end of the boost.

Several different families of J.T.V. were made to work reliably, and it finally became the first British missile to be ram-jet sustained in supersonic flight. It was flown with tandem boosts, overlap boosts and wrap-round boosts in a variety of positions and successful boost separation of all these variants was achieved.

3. Basic Engineering Decisions

While the development of basic techniques was in progress, a second working party was considering the missile design. Numerous configurations were studied and a further year passed before the final choice of design was made.

FIGURE 3. J.T.V.1 on launcher.

Among the factors taken into account were: —

Radome aberration

A supersonic missile which flies for any distance must, if its weight and cost are to be economic, have a streamlined radome in front of the homing eye.

This radome causes distortion of the radiation reflected from the target and this manifests itself in an erroneous line of sight. If the radome is rotated in space the line of sight erroneously rotates also. This conveys false steering signals to the missile, whose effect can be very serious at high altitude.

Manoeuvrability

A compromise has to be struck between available manoeuvre, and time required to develop that manoeuvre, at high altitude.

Packaging

It was most desirable, from the point of view of ease of development and also of Service handling, that the missile should divide into different types of unit which are as independent as possible, both physically and functionally. In particular, development of each unit can then proceed at the highest possible rate, with the minimum of mutual interference.

Stretch

It was essential that the missile should be capable of having its range increased without appreciable re-design.

Electronic components

Sub-miniature components were selected from the outset, although they were not at that time fully developed.

3.1. MISSILE DESIGN

3.1.1. *Ram-jets*

There existed a choice between three basic arrangements: —

(*a*) Integrated ram-jet and body-nose intake (Fig. 4).
(*b*) Integrated ram-jet and body-side intakes (Fig. 5).
(*c*) Multi-ram-jet (Fig. 6).

Design (*a*) was rejected because of lack of space for guidance and on grounds of vibration. Design (*b*) was rejected on grounds of lack of experience of side intakes in interceptor missile configurations. This left design (*c*) as that to be developed, and this design requires short ram-jets with consequent intake and combustion problems. These difficulties were accepted.

3.1.2. *Auxiliary power supplies*

In view of the requirement for long range it was decided that these should all be operated by simple ram air turbines fed from small air intakes and exhausting through the back of the missile. Thus auxiliary power is available no matter how long the missile flies. Initially there were three turbines—one for hydraulic power (Fig. 7), one for fuel pumping, and one for electrical power. This number was soon reduced to two.

3.1.3. *Wings*

Once it had been decided to adopt the multi-ram-jet configuration it was clear that more than one ram-jet had to be mounted on the missile body. The question remained as to how many wings the missile should carry and whether these should be fixed or moving.

It was certainly true that with numerous wings, ram-jets and tails to mount, the body was in danger of looking like a Christmas Tree. Nevertheless, some fairly reasonable paper designs were produced as combinations of the following: —

Fixed wings	:	moving wings
Two ram-jets	:	four ram-jets
Cruciform	:	monoplane

A comparative study was made of the performance of these designs, particularly from the point of view of interception accuracy.

For a given missile weight, the number of ram-jets made little difference to performance. The available manoeuvre of the cruciform fixed wing and monoplane moving wing missiles was much the same, a monoplane fixed wing having best manoeuvrability of all. Response times in pitch were much shorter for the moving wing designs, while the fixed wing designs suffered from radome aberration effects.

The best overall compromise was considered to be the monoplane moving wing, which had moderate manoeuvrability and quick response while not suffering too much from the effects of radome aberration. This configuration was neatest with two ram-jets.

The use of a monoplane configuration for a guided missile is sufficiently unorthodox to require some discussion.

3.1.4. *The Monoplane missile*

A Cartesian missile manoeuvres so as to achieve a collision course separately in each manoeuvre plane. The miss distance can be increased by missile response lags and by cross couplings, such as those between pitch and yaw manoeuvre affecting the roll stabilisation upon which the system fundamentally depends.

A twist and steer missile rolls so as to align the normal to the wings with the vector direction in which manoeuvre is required, and develops the manoeuvre by pitching. The only major cross couplings are gyroscopic forces.

Much remains to be said on the philosophical difference between these systems. Certainly the twist and steer arrangement is the one favoured by Nature in

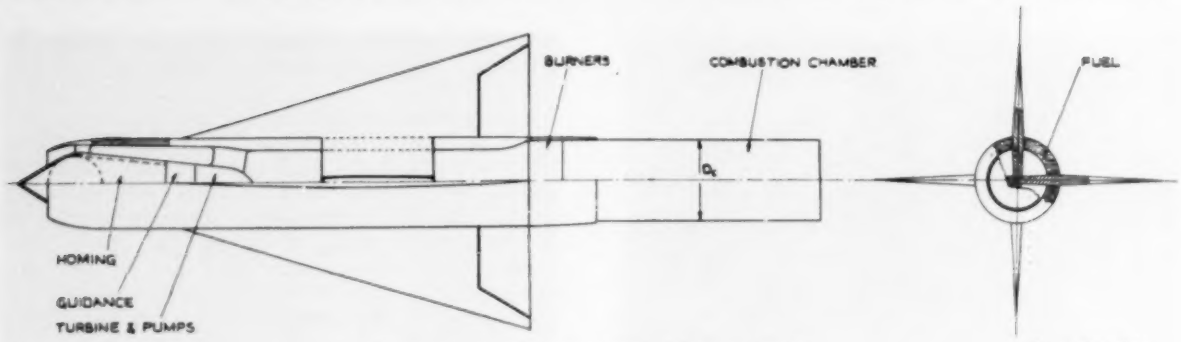

FIGURE 4. Integrated ram-jet and body-nose intake.

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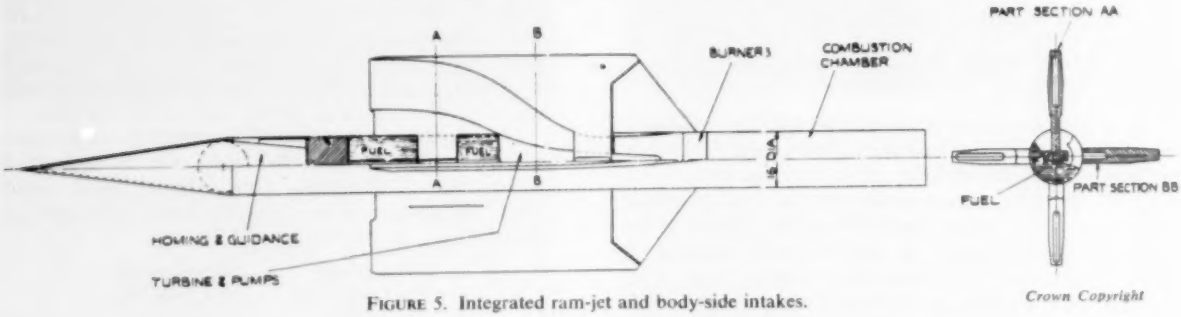

FIGURE 5. Integrated ram-jet and body-side intakes.

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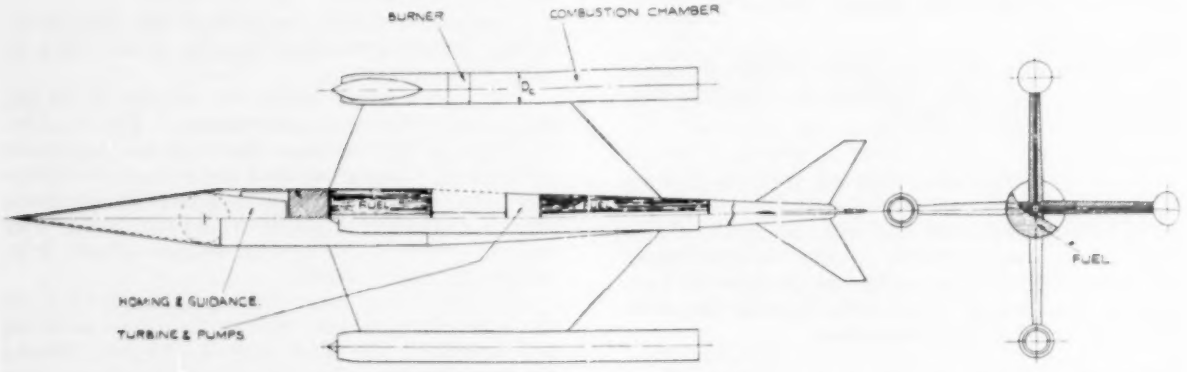

FIGURE 6. Multi-ram-jet weapon.

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all birds and nearly all fish. It does possess the advantage of being redundant, in that a failure of either pitch or roll control can still result in some sort of interception course, whereas a failure in one plane of a Cartesian missile is catastrophic.

The characteristic time lag in roll response of a twist steer missile can be made much less than that in pitch. One might expect that a more accurate interception would therefore be possible and this is true, provided that resonance instability due to gyroscopic forces is avoided by suppression of body motion in a moving wing missile. Otherwise, the roll rate may have to be kept below the pitch or yaw frequency, and the miss distance performance will then not be superior to that of a Cartesian system, except for reduction of cross couplings. (This does not necessarily mean, however, that the kill probability is not higher.)

The theory of the twist-steer system is not easily tractable with Cartesian mathematics, since superposition principles cannot be used. The availability of electronic digital computers has done much to reduce this difficulty.

3.1.5. *Wing and body size*

It was necessary to strike a compromise in design between wing size (and hence altitude manoeuvrability) and homing eye size, since increase in size of homing eye gives better target position information, and thus calls for less missile manoeuvre. This compromise was influenced as far as possible in the direction of homing eye size, since this also improves range of target detection.

3.1.6. *The chosen missile configuration*

Figure 8 shows the missile configuration adopted as a result of these studies. It closely resembles the present

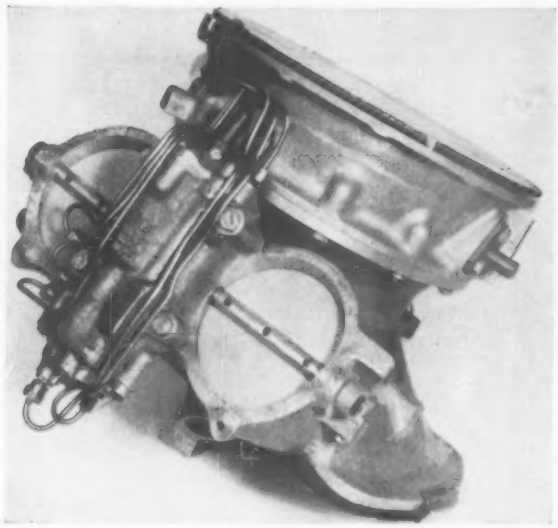


FIGURE 7. Turbo-pump unit.

Bloodhound missile, with the exception of a change in the tailplane arrangement. (Associated with this tailplane is a different boost arangement.)

Design and development of this missile then began. Despite the late start, it appeared possible that the time scale might match that of the other earlier projects.

4. Engineering Development and Technique

4.1. FAMILY OF TEST VEHICLES

Five different types of test vehicle were used in the development before the weapon stage was reached.

X.T.V.1. 1/4 scale model (Fig. 9).
X.T.V.2. 1/3 scale controlled model (Fig. 10).
X.T.V.3. Full scale unpowered missile (Fig. 11).
X.T.V.4. Full scale ram-jet propulsion test vehicle (Fig. 12).
X.T.V.5. Complete experimental missile, with homing head (Fig. 13).

These test vehicles explored all the techniques necessary for production of a weapon, and the final one (X.T.V.5) closely resembled the present Bloodhound missile (Fig. 24).

4.2. BOOSTING AND BOOST SEPARATION

When the problem of boosting Bloodhound was first considered, the " wrap-round " boost arrangement now used was not possible because of the interdigitated missile fins of the original configuration. Forward mounted wrap-round boosts would have interfered with homing, also experience on J.T.V. indicated that boosts in this position might have unfavourable effects on the ram-jets. Thus the obvious choice was a tandem arrangement with a single large boost motor of about 26 in. diameter, mounted behind the missile.

On the first and smallest test vehicle, the quarter scale X.T.V.1, there were three five-inch diameter boosts grouped in a single cluster behind the missile in the tandem arrangement. A number of wingless rounds were fired successfully. Later rounds with wings failed in the boost phase due to a transonic instability through excessive flexure and slop of the boost to missile connection—despite plenty of "rigid body" aerodynamic stability. This highlighted the basic problem of tandem boosting—the difficulty of obtaining adequate structural stiffness in the joint. With the small body base diameter this was obviously going to be nearly impracticable on the full size missile. Even when transonic stability is achieved, the missile is likely to be damaged by the kick when the boosts separate from the missile since the destabilising effect of body flexure is, in general, most severe at the maximum speed. Some later tandem-boosted test vehicles failed in this way.

Following the X.T.V.1 failures the boosts were divided into two clusters, one on each side of the missile body, and moved up to the trailing edge of the wing. The clusters were pin-jointed together at their aft ends and attached to the missile body at two points as far apart as possible to give a good structural connection between missile and boosts. This "overlap" boost arrangement was never very tidy, but it was a simple system to engineer—the stiffness is inherently good and the clearance between the missile and boosts not critical in the separation phase. Separation is straightforward, as the boost thrust dies away the boost slides back along the missile. This movement automatically disengages the attachments to the missile and the two clusters open out, pivoting about the pin-point, assisted by lifting vanes on the nose of each cluster.

The overlap arrangement was first used on the third scale X.T.V.2, and was used in various forms on all

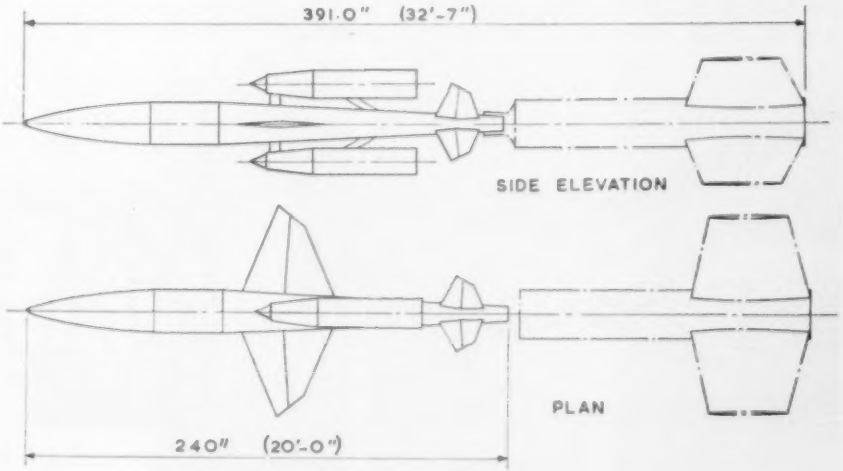
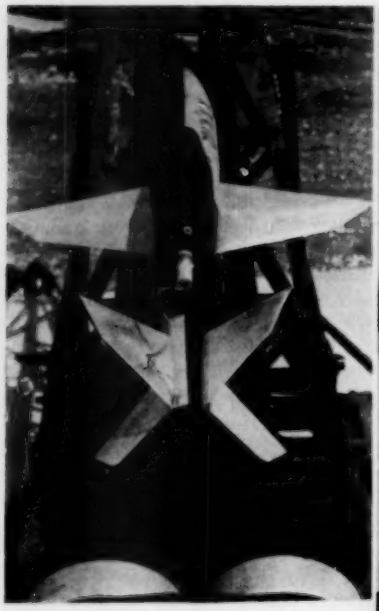


FIGURE 8. Original chosen missile configuration.



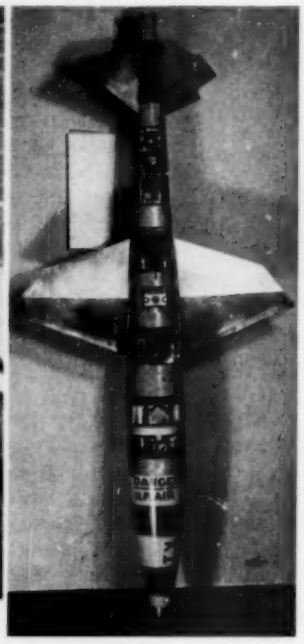


FIGURE 9 (*above*). X.T.V.1.
FIGURE 10 (*right*). X.T.V.2.

full scale test vehicles (Figs. 11, 12 and 14) until the subsequent change to in-line missile fins. Fig. 12 shows six boosts on the first X.T.V.4, Fig. 11 four boosts on an X.T.V.3. A typical overlap boost separation sequence is shown in Fig. 15.

When the missile configuration changed, the present, much more compact, arrangement of aft mounted wrap-round boosts (Fig. 13) became possible. It was first used on X.T.V.3. Later it was used in various forms on X.T.V.4, X.T.V.5, and the production missile. In the early stages a number of difficulties were encountered, the most serious of which was damage to the missile during boost separation.

In theory, separation of the boosts from the missile is quite simple. All four boosts are interconnected by a ring at their aft ends so that as the thrust dies away they slide back together along the missile. This releases the forward attachments and the boosts open away from the missile, each pivoting about the interconnecting ring. At the same time the whole boost assembly continues to move back away from the missile. Fig. 16 shows the separation sequence.

The problem of boost separation lies in obtaining a nice balance between the opening spin of the boost—which causes their aft ends to move forward—and the rearward movement of the whole boost assembly. Eventually, by adjustment of the size of lifting vanes on the boost noses, completely reliable separation was achieved and theoretical techniques were developed so that separation of new wrap-round configurations could be successfully predicted.

4.3. PROPULSION DEVELOPMENT

The initial phase of propulsion development was concerned with providing a ram-jet, with simple fuel controls, to power test vehicles for control and homing tests. Under an agreement with Boeing Aircraft a team from Bristol Aero Engines Ram-jet Department went to the U.S.A. where the joint Bristol-Boeing team designed the B.B.1, a sixteen-inch diameter ram-jet. Two such ram-jets were to provide longitudinal acceleration away from boost separation following subsonic lightup. Within nine weeks of design completion the first B.B.1 engine had been manufactured, shipped to America, and had developed full thrust under test.

The early propulsion test vehicles were boosted to only a low supersonic speed and wings, therefore, were not flown on them. This helped the separation thrust-drag margin, but made cruising at required Mach numbers impossible. The intake lip was therefore extended to reduce the mass flow and when combustion difficulties were overcome this unit gave very satisfactory service for a large number of development missiles up to altitudes of about 30,000 ft., when rich extinctions occurred.

About sixty propulsion vehicles were required to prove this standard, as ground rig facilities were limited. The problems solved during this period included a series of lightup failures due to over-fuelling. The solution of this problem led to the assembly of ground rigs with

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FIGURE 11. X.T.V.3 on launcher.

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FIGURE 12. X.T.V.4 on launcher.

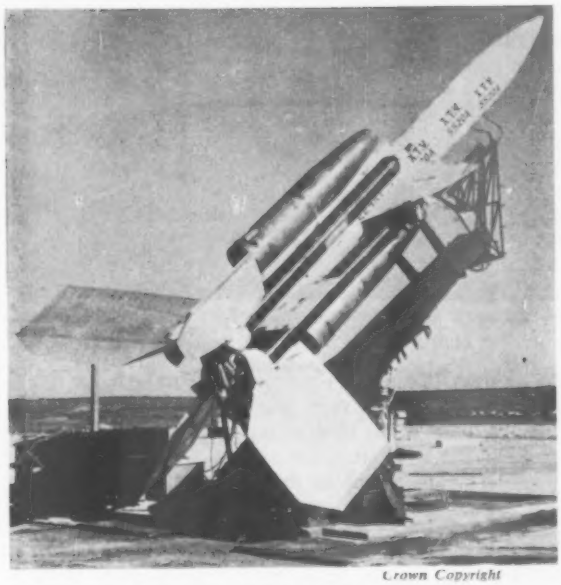

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FIGURE 13. X.T.V.5 on launcher.

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FIGURE 14. X.T.V.4 with four overlap boosts.

slotted nozzles to simulate boost phase conditions. Severe banging at a Mach number of 2·0 showed that the ram-jet island needed lengthening to provide more gentle diffusion to remove unstable separated flow. The mechanism of the banging was such that combustion took place alternately in an annulus downstream of the outer ring of flares, followed by a relight aft of the central flare. A test vehicle flown without the central flare proved this when a straight extinction occurred, the mixing length of the fuel was decreased at the same time and reliable combustion achieved.

The first weapon-type ram-jet flown with fuel controls was developed from this test vehicle experience. In due course nearly every feature of the ram-jet was redesigned. Numerous test vehicles were necessary to explore the operating conditions for the homing weapon. These led to the production Thor-type ram-jet (Fig. 17) which has proven combustion over a wide range of fuel-air ratios, to match the various conditions met within homing flight, up to high altitudes. Adequate thrust-drag margin is provided at the separation Mach number and the major part of the flight is controlled to the required Mach numbers. Fig. 25 shows the Thor-type ram-jet in flight.

4.4. AERODYNAMICS

The bases for a twist-steer configuration have been given. Effort during the first three years was spent in evaluating actual aerodynamic parameters to see, for example, how small a body incidence could be achieved during pitch manoeuvre. Basically, the tailplane area and wing to centre of gravity position could be varied, the second to a more limited extent due to the possible adverse ram-jet intake interference arising from wings at high incidence. Moving tails were dropped fairly early on, after a study of overall stability showed that body to wing angle ratios would be good enough without them.

Third scale flight models and wind tunnel tests showed that the early cruciform 45 degree tail design was

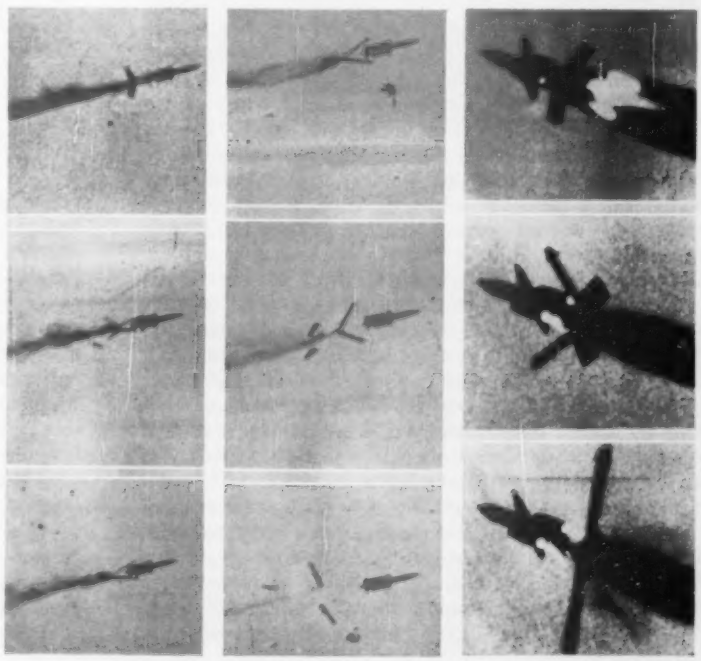

FIGURE 15 (*left*). X.T.V.4. Boost separation sequence.
FIGURE 16 (*far right*). Wrap round boost separation sequence.

Both illustrations Crown Copyright

noticeably unstable in pitch at high wing angles. The vortex sheet caused considerable loss of efficiency and a large movement of wing lift centre of pressure. It was realised that a more linear system would be obtained from in-line fins, if the tail span was kept to about half the wing span. The tapered wing results in a fairly smooth downwash pattern, except for a region behind the tip, and with a low span tail, large changes of static stability would be avoided at low incidence. At high wing angles it was hoped to trim the missile to allow the tailplane to avoid the vortex sheet. This has been achieved simultaneously with the correct value of wings fixed weathercock frequency.

The change of wing lift centre of pressure with wing angle over full angular travel is about the same as that with Mach number over the operating range of the missile. This is, of course, due mainly to changes in downwash and carry-over lift on to the body, with wing panel centre of pressure remaining sensibly constant. The downwash is quite large, and it is of interest to note that even so, the wing is still pivoted near the centre of gravity. This is because the carry-over lift is not only effective on the body adjacent to the wings but the pressure field extends over the ram-jets, giving an additional couple, and effectively moving the carry-over centre of pressure well behind the wings.

The 45 degree inclined tails proved impracticable for another reason. The close proximity of the ram-jet tailpipe probably caused some loss in efficiency anyway, and the turbulent jet efflux certainly had a de-stabilising influence. An early propulsion test vehicle was lost by going unstable at the critical Mach number due to this effect. The magnitude of the pressure load was also realised when a third scale test vehicle with cruciform tails, and employing a rocket sustainer inside dummy ram-jets, pitched in the reverse direction to that expected when one sustainer failed.

The wings, designed for pitch, give more than adequate roll control. (If the control system required it the missile could manoeuvre an order faster in roll.) Rolling movement due to combined pitch and yaw can be easily overcome. The linearity of the downwash pattern is underlined by the fact that the rolling due to wing angle and yaw is negligible, it is only in the wings fixed pitch incidence and yaw case, with a sizeable wing root vortex system, that the rolling moment is significant.

Apart from the example given above, cross-derivatives were made the subject of an intensive study at an early stage. The results have been limited, as the techniques, both in flight and in tunnels, have not been developed to deal adequately with rate terms. Theoretical methods have had to be resorted to, extending the steady state cases by analogy. Over a hundred cross-derivatives were examined. None was found to be of serious importance.

The body shape was originally designed for minimum drag for a given volume and given body diameter. The absence of a body mounted sustainer enabled a tapered rear-body to be designed. This taper has a favourable interference drag from the ram-jet lip shock, particularly at low Mach numbers, where it assists the thrust-drag margin at separation. Although the wings to a large extent avoid interfering with the ram-jet intake, there is an inverse interference, the lip shock striking the wing at some speeds. The difference in position of this shock as the wing inclines causes a lift which alters the wing centre-of-pressure. The lift to a certain extent cancels the losses as the root gap grows with increasing incidence.

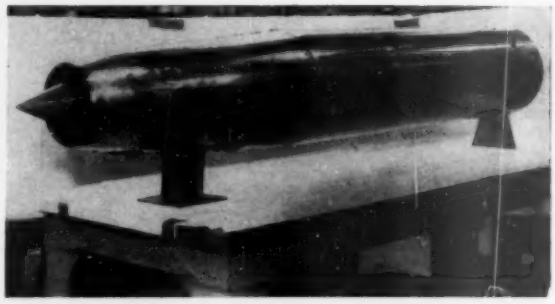

FIGURE 17. Thor-type ram-jet.

Any wing to auxiliary intake interference problem has been removed, however, by careful design modifications which solved the boost interference troubles encountered on Bloodhound test vehicles.

During a homing mission the missile sheds its boosts at around 2,000 ft., having dropped very little in angle during the boost phase. The launch stability margin is small, which reduces wind dispersion to a minimum, comparable with the random dispersion arising from the boost thrust behaviour. On a flight to medium or long range the missile then accelerates to cruise speed in a few seconds.

4.5. AEROELASTICITY

It is a well established fact that, as well as having to consider the usual aeroelastic problems of flutter and divergence, it is necessary for the aeroelastician to give some thought to the effects of structural deformation on the missile response to control system demands and the resulting manoeuvres, both transient and steady-state.

On the Bloodhound missile, it became apparent that the effects of structural deformations would have to be taken into account when considering the stability of the control system at frequencies in the vicinity of the weathercock frequency; also the steady-state aerodynamic forces could be affected. Although the former problem is dynamic in nature for the Bloodhound, it can be treated on a static basis by calculating the effects of structural deformation on the aerodynamic stability derivatives.

Since the Bloodhound missile is a moving wing missile with fixed tail surfaces, the aerodynamic derivative to be most influenced by structural deformation is the pitching moment due to the wing lift.

On the early Bloodhound test vehicles, when little regard was paid to the problem, it was found that, although the tailplane efficiency was fairly high and thus contributing a positive amount to the pitching moment, the body stiffness was so low that the total

aeroelastic correction was large and negative. In addition, it was found by structural tests that the missile body deformation was extremely non-linear with load, and that the body stiffness varied considerably from missile to missile. Thus the aeroelastic correction varied from missile to missile and was dependent on the magnitude of the forces acting on the missile. This was not a very satisfactory state of affairs.

For the later Bloodhound test vehicles and the production missile itself, it was obvious that a more positive value of the aeroelastic correction was required. To achieve this and, at the same time, a higher fundamental body bending frequency which was required to obtain better stability of the control system at high frequencies, the body stiffness was increased. At the same time, steps were taken to minimise the variation of stiffness from missile to missile and the non-linearity of body deformations with load.

4.5.1. *Wing divergence*

During flight tests on early test vehicles of the X.T.V.3 and X.T.V.4 series to investigate aerodynamic stability, five of the vehicles broke up in the transonic region of the boost phase. Various reasons for this, including the obvious one of lack of aerodynamic stability, were considered. Two of the missiles had the same centre of gravity position as missiles which had flown successfully, while the c.g. position on the other three missiles had been farther aft.

On the fifth failure (Fig. 18) the port wing was observed to fail and become detached from the missile just before the total destruction of the missile, and it was obvious that the cause of the previous failures had been aerodynamic instability caused by excessive aeroelastic deformation of the wing. A subsequent analysis revealed that the wings used on these missiles were not particularly stiff in torsion and, since the c.p. position is well forward at high subsonic and transonic speeds, it was shown that the wings had diverged or, at least, had been very near to the actual divergence condition in the high subsonic to low supersonic regions of flight.

On subsequent rounds, the wings were replaced by wings of a different construction having a higher torsional stiffness and no further failures occurred.

4.5.2. *Flutter*

Except for the problems connected with the stability of the control system at high frequencies, which have been discussed elsewhere, flutter incidents on Bloodhound test vehicles have been few and far between. In fact, there is some doubt whether they were true flutter incidents.

During the boost phase of one incomplete Bloodhound test vehicle, an oscillation having a frequency of 6-8 c./sec. developed in the pitch plane. The amplitude of the oscillation increased from zero to a maximum of about $\pm 6g$, and then showed a tendency to damp out. The onset of the oscillation practically coincided with the detonation of lateral thrust units in the yaw plane. A little later, at separation, failure of the round occurred.

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FIGURE 18. Wing divergence sequence.

The fundamental body bending frequency of the boosted missile was low and it was thought that the fundamental mode had coupled with the rigid body modes to reduce the aerodynamic damping and thus give rise to a flutter condition. However, theoretical calculations never succeeded in predicting such flutter, although it was shown that the removal of ballast from the nose would result in a decrease of the aerodynamic damping. This particular round had less nose ballast than previous rounds of the same build and, therefore, it was deduced that this explained why earlier rounds had not shown a tendency to flutter. The calculations also showed that if the fundamental body frequency were raised, then the aerodynamic damping in the appropriate mode was increased.

As a result of this investigation it was decided that future rounds must either carry a minimum amount of nose ballast, or have increased body stiffness. No further incident occurred.

On two early moving wing missiles, divergent torsional oscillations developed on the wings at low supersonic Mach numbers leading, in the case of one missile, to failure. It was suspected that one degree of freedom torsional flutter had occurred and a subsequent theoretical analysis, using two-dimensional second order aerodynamics, did show that the torsional stiffness of the wings concerned was sufficiently low to cause this type of flutter; flutter in a single torsion mode can occur in theory, since at low supersonic Mach numbers and low frequency parameter, the two-dimensional torsional aerodynamic damping moment is negative, but there are doubts whether this type of flutter can occur in practice when an allowance for three-dimensional and thickness effects is made. Consequently, since these two missiles had moving wings, some consideration was given to the possible loss of stiffness and damping in the control system and a number of impedence tests were arranged. Unfortunately, the results of these tests were inconclusive, but it seemed likely that with a favourable impedence of the servo, flutter even of bending-torsion type, may have occurred. Later rounds had wings of increased torsional stiffness and no further incidents were observed.

An interesting case of buffeting occurred during the flight of a round whose main purpose was to prove a new type of boost rocket. The nose cone of the port lower boost became detached and, immediately afterwards, the fin on the same boost tube started to oscillate in a bending mode and failure of the fin followed. It is believed that the oscillation of the fin was caused by a vortex sheet leaving the bluff end of the boost after the nose cone had become detached. The frequency of the oscillation was very near the boost fin fundamental bending frequency and consequently it is not surprising that the fin failed. The detachment of the nose cone was attributed to a lack of strength in its attachment. As a consequence the boost nose cones were strengthened.

4.6. STRUCTURAL DESIGN

4.6.1. *Material choice*

All the materials used are readily available and not strategic. Structurally the choice depends on strength/weight ratio (in the case of tension members) and on (tangent modulus)$^{1/n}$/(weight) ratio where n is 2 or 3 for compression members and one for stiffness requirements. In other parts the dimensions are fixed by attachment problems or manufacturing difficulties and these require low density structural materials. Since cost is vital it is desirable to keep the structure as simple as possible and to reduce the number of final assembly operations. This has led to the employment of magnesium alloy castings for many items. As much as possible of the nearby complication in the way of mounting brackets and pipes is built into the basic castings. The magnesium alloy corrosion protection problems have had to be faced but this has been found to be well worthwhile.

Consequently there are no fabricated bulkheads in Bloodhound, all are one-piece magnesium castings usually doing several jobs. The remaining primary structure is mostly conventional aluminium alloy, which is satisfactory for the temperatures and times involved. Steel is used in a few special places. Plywood has been found very satisfactory as a matrix for wings and fins.

In the production boost assembly the venturi is an interesting example of the use of plastics for weight saving. This is a Durestos lined aluminium alloy forging which also functions as a mounting for the boost motor and boost fin.

4.6.2. *Design for strength and stiffness*

As previously mentioned a special difficulty is that in the pitch plane a definite stiffness is necessary. Further, it is essential to keep the missile to missile variation of stiffness as small as possible. It was decided that the satisfaction of these requirements is best reached by using "backbone" members running along the top and bottom of the body with as few joints as possible, those joints that have to exist being made with tension bolts. It has been found that this method of construction gives quite good agreement with stiffness predictions.

Wing, tailplane and boost fin construction using plywood matrices sandwiched between aluminium alloy skins and mounted on spigots extending from the root has been found most satisfactory. It combines ease of construction, particularly at the development stage, with low weight.

A certain amount of structure weight has been expended to achieve simplicity. The penalty in using thicker skins, rather than stiffeners or more frames, seems to be small and has generally fitted better with the stiffness requirements. It also leads to more usable volume.

4.6.3. *Kinetic heating testing*

It has been found essential to ground test components under the full flight temperature environment; prediction of the exact strength and stiffness under combined loading and kinetic heating is not feasible for such a structure. Earlier attempts used electric blankets. These were moderately successful, but inflexible in design, expensive, and time consuming in manufacture, needing, for example, hand stitching. All the major components are now tested using infra-red lamps, mounted in polished copper reflectors (Fig. 19). The temperature of parts of the skin away from frames is controlled to the theoretical estimate for the worst flight case, using a special controller. This uses a motor-driven cam to demand the temperature and a servo uses the error between the control thermocouple outputs and the demanded temperature. Variation of heating requirements over frames, and so on, can only be approximated by varying the number of lamps per square foot. This method of control has been found accurate and stable and the whole of the structure has been tested in sections corresponding to the maximum power of the plant. A system of remote reading dial gauges has been devised for stiffness measurements. These and the temperature gauges are photographed at intervals during a test run.

4.7. KINEMATICS AND DYNAMICS

Pitch and roll manoeuvre are obtained from the

moving wings which operate symmetrically to produce a normal force and symmetrically to produce a rolling moment, using appropriate feedback controls. The pitch error signal, suitably shaped, actuates the wings symmetrically.

The roll loop is a little more complicated. This missile is in the correct roll position when the yaw steering signal is zero. The control input is a demand for roll which is compared with achieved roll. With suitable shaping this operates the wing servo mechanism to produce a differential wing angle.

The basic speed of response of the pitch loop is the time for the powerful wing servos to put on a wing angle and hence is basically very fast. Since the c.g. of the missile and the centre of pressure of wing lift are close together, little body motion is induced.

In roll very powerful roll moments are applied by the wings acting differentially and, the roll moment of inertia being of a much smaller order than the pitch and yaw moments of inertia, very high roll accelerations and rates can be achieved. There being no stability problem analogous to weathercock instability, the basic speed of response can be achieved in practice making the roll system much faster than the pitch system. Further, by altering the gain of the roll loop with altitude, the roll response of the missile can be maintained almost independent of altitude.

As will have been noted the basic controls of Bloodhound are in pitch and roll. There is in fact no yaw control. With the very unequal pitch and roll moments of inertia there is some cross coupling into yaw. Similarly there are aerodynamic cross couplings due to combined pitch and roll. In spite of the large roll rates, with small pitch incidences and the small aerodynamic cross coupling derivatives there is no significant aerodynamic cross coupling problem. Yaw manoeuvres of the missile have been small.

For an elastic structure like the missile, disturbance in flight will result in excitation of the normal modes of vibration of the missile. The resultant oscillations will be detected by the feedback instruments in the roll and pitch loops and fed to the control surface servos. These fast servos have a considerable output even at quite high frequency and are capable of appreciable provocation of the fundamental body modes, thus completing parasitic loops in both pitch and roll. Our early flight experience indicates that this is a very real problem and structural failure can quickly ensue. Many measures can be adopted to alleviate this problem, and these proved effective in preventing a recurrence.

A twist/steer missile has only one plane in which it can apply acceleration normal to its flight path. It navigates therefore by rolling so that this alone coincides with the direction of the required manoeuvre.

It is interesting to compare the roll requirements of a homing system with a beam-riding system. With the beam-riding system the missile is aware of its vectorial distance from the centre of the beam but is not fully aware of the rate at which it is crossing the beam. In the case in which the missile is approaching a stationary target, but performing a clockwise helical motion when the missile is vertically above the centre of the beam and crossing it, the beam rider would get a demand vertically downwards. In the same circumstance the homing missile is aware of the heading error and gets a demand with the same vertical component but with a component to the left as well. The beam rider would get a demand in this direction later when it has proceeded farther round the helix; so that there is a phase advance effect for the homing missile compared with the beam rider. This phase advance is a spiral breaking signal so that there is less proneness to spiral courses in the homing system. Since the roll lags in the twist/steer missile are smaller than in the equivalent Cartesian missile, the twist/steer missile is even less likely to indulge in spiral courses.

The requirement for a fast roll loop has been fully demonstrated in theory and flight trials. The present control system has a fast roll rate response. (An earlier control system had a drag cup motor resolver which, by imposing an extra integration, made the response much slower.)

One of the difficulties in assessing the performance of a homing missile lies in appreciating its behaviour in a three-dimensional picture. The concept of the boresight plane has been found very useful in this context. The boresight plane is a fixed plane through the impact point perpendicular to the ideal constant bearing course of the missile. At any time the tangent to the flight path intersects this plane. The locus of this intersection

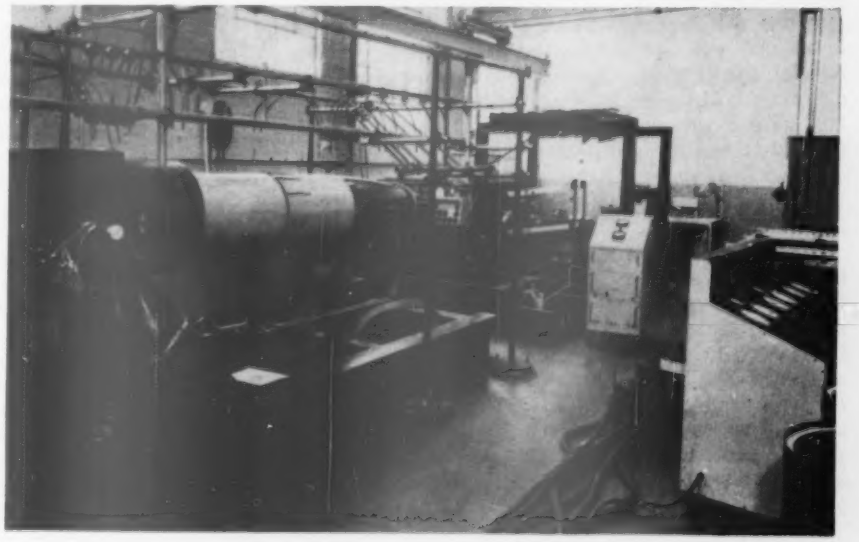

FIGURE 19. Kinetic heating test, showing missile, thermocouple gauges, temperature control unit and loading control panel.

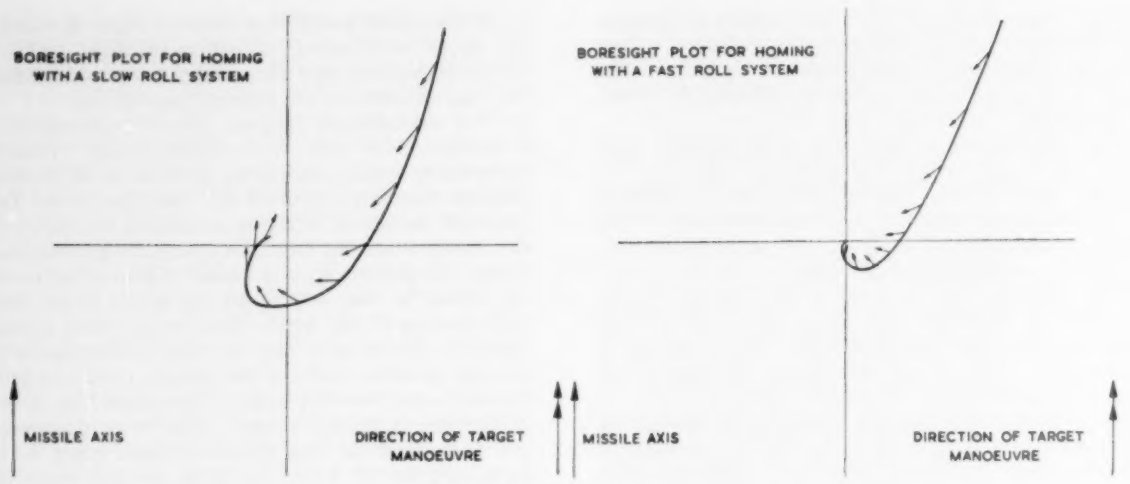
BORESIGHT PLOT FOR HOMING WITH A SLOW ROLL SYSTEM
MISSILE AXIS
DIRECTION OF TARGET MANOEUVRE
BORESIGHT PLOT FOR HOMING WITH A FAST ROLL SYSTEM
MISSILE AXIS
DIRECTION OF TARGET MANOEUVRE

FIGURE 20. Boresight plots.

gives a two-dimensional representation of the missile course which is very helpful. Immediately available from this plot is the total acceleration demand and the ideal roll attitude. Velocities in the boresight plane are proportional to missile accelerations. The boresight plots shown (Fig. 20) indicate both the usefulness of this method of representation and the effects of fast and slow roll loops on missile performance.

It is apparent from the very beginning that a twist/steer missile system is essentially a non-linear system. Hence any ideas obtained from linear calculations have to be treated with great care. Although some work can be done treating pitch and roll as separate modes, it is soon clear that couplings into yaw must be considered. In the Cartesian missile system it is much less evident at first that the system is non-linear. In the tail control case, where the pitch and yaw incidences are inherently large and the couplings powerful, it may well be the case in the end that the Cartesian system is more non-linear. Certainly in such systems it is found necessary to control the third mode, in that case roll, where it is unnecessary in Bloodhound to control yaw. Considerable simplification of the missile ensues and, in fact, the non-linearity is deliberately increased by the introduction of the very non-linear control units. In addition, these units permit the acceptance of basic instabilities which appear only as small oscillations. Bloodhound's control system is "unstable" in several ways, none of which matters in practice.

The acceptance of the non-linearity of the Bloodhound missile at an early stage led to an early interest in simulation of the missile. Digital and analogue models of the missile and parts of the missile have been found extremely valuable in understanding the system and evaluating the meaning of flight trials. Perhaps the best example of the use of simulation is the diagnosis of the faults in the early homing rounds with poor roll performance and the influence of biases in the control system on the course and miss distance of the early rounds.

4.8. THE DESIGN OF ELECTRONIC EQUIPMENT FOR THE BLOODHOUND GUIDED MISSILE

4.8.1. *Design philosophy*

Before the actual design of the guidance and control electronics for Bloodhound was started, the following assumptions were made and the design philosophy based thereon: —

(*i*) That the number of actual catastrophic valve failures in flight would be small and that most valves would continue to work although their performance might deteriorate;

(*ii*) That, due to the severe environmental conditions of vibration and acceleration, the valve characteristics might change in flight and there would probably be a fairly large, but at that time, unknown, microphony output;

(*iii*) That the types of valves chosen must be such as to minimise the chance of failure and the microphony output.

Accordingly, it was decided to use the sub-miniature range of valves wherever possible, since these had the smallest and strongest glass envelopes and their structures, being smaller and more rigid, would have smaller amplitude and higher frequency resonances which would make the design of anti-vibration mountings easier to accomplish.

It was decided to design the electronic circuits so that each valve had the minimal functions to perform and so that, within reason, the circuit would continue to function satisfactorily even though the valve parameters changed. This meant that no attempt was made to reduce the number of valves used by applying trick circuits where one valve had a multiple function.

4.8.2. *Mechanical layout and construction*

Because of frightening stories about vibration, a very solid and compact block type of construction was employed (Fig. 21) and an attempt, soon dropped, was made to do without plugs and sockets entirely. Potting of circuits was tried and dropped because of the effort required and the expense—it is now found that potting

tends to pull the components apart. Block construction was expensive and difficult to manufacture and faults were difficult to locate and remedy. Hence it was dropped and a more open layout based on printed circuits adopted (Figs. 22 and 23).

4.8.3. *Control system*

A d.c. system was used initially, but drifts arising in numerous places led to use of a large number of correcting potentiometers.

This experience caused an a.c. system to be adopted for Bloodhound.

Conclusion

The electronic circuits used in Bloodhound have been designed to make the best possible use of the valves available, and it must be pointed out that lately the valves provided have shown themselves to be very well designed and reliable components.

Some few valves which are within the manufacturers' specification limits will be rejected due to extra tight test limits set by the missile designers, but it should be realised that these few rejects together form a very small price to pay to get improved performance and reliability from a missile costing many thousands of pounds.

4.9. SEEKER AND ELECTRICAL POWER SUPPLIES

4.9.1. *The experimental and final seekers*

The experimental seeker (Fig. 21) was basically the C.T.V.4 receiver spread out a bit. Plugs and sockets were not liked but limited use of them was essential. Soldered joints can be the cause of many faults and extreme care and very thorough inspection is necessary —*every joint inspected*.

The development of drift-free silicon diode phase sensitive rectifiers was a major advance. They led to the use of d.c. for precessing the dish gyro, with a resultant increase in precession torque and lower centring torques. The output of the head was now d.c., hence changes in the control system followed automatically.

More experience showed that valves were still not satisfactory in certain critical places—these were replaced by transistors.

4.9.2. *Sources of power*

Early studies showed that power requirements were greater than could be supplied by batteries. (In any case battery development for this purpose was in a very early stage.) An alternator was chosen.

Continuity of power supplies from target acquisition was considered desirable, since a change over of source of supply may cause disturbance resulting in loss of lock. Use of stored energy may be a limitation of flight durations. If ram air had been used directly to generate electrical power, storage during boost would have been difficult and a wide range of air pressure would have made voltage and frequency control to narrow limits difficult. The use of oil as an intermediate medium made energy storage and ground running easier and allowed two stages of control—rough control of oil pressure and fine control of alternator speed by means of an oil servo valve.

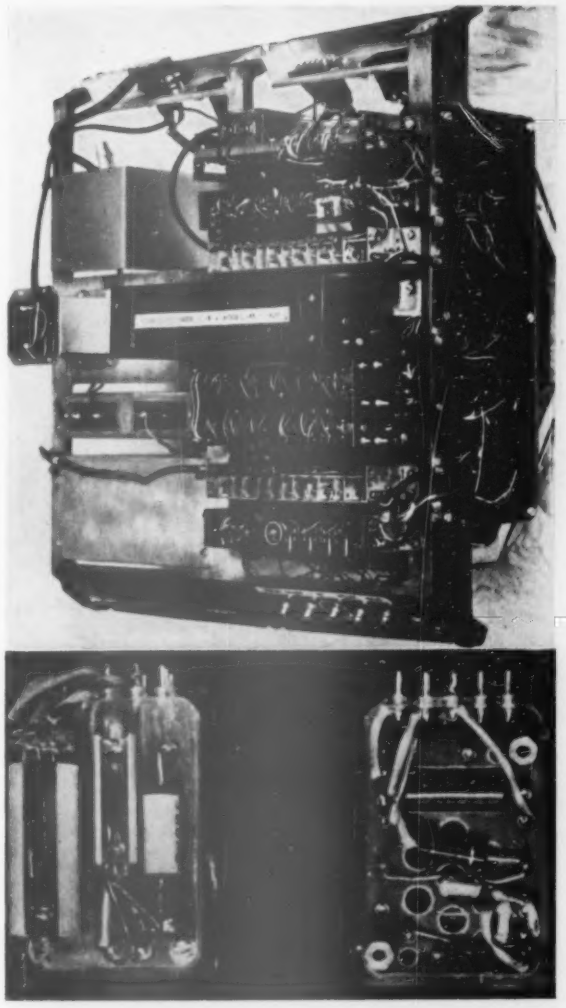

FIGURE 21. Experimental guidance assembly, and potted component.

4.10. TESTING

Experience has shown that it is essential that all units be drop tested before being flown. It has been proved that centrifuging does not show up the type of fault that will occur in flight. Vibration testing of units is essential as a development technique, but the severity of this test means that units cannot be flown afterwards.

There are four levels of testing: —

(*a*) *Components*

All bought out components are tested to specification.

(*b*) *Sub-assemblies*

(Consist of a single circuit element with about six valves.)

Tested electrically.

Drop tested and monitored for disturbances.

Spot checks after drop test.

(*c*) *Assemblies*

(Consist of about 20 sub-assemblies, *e.g.*

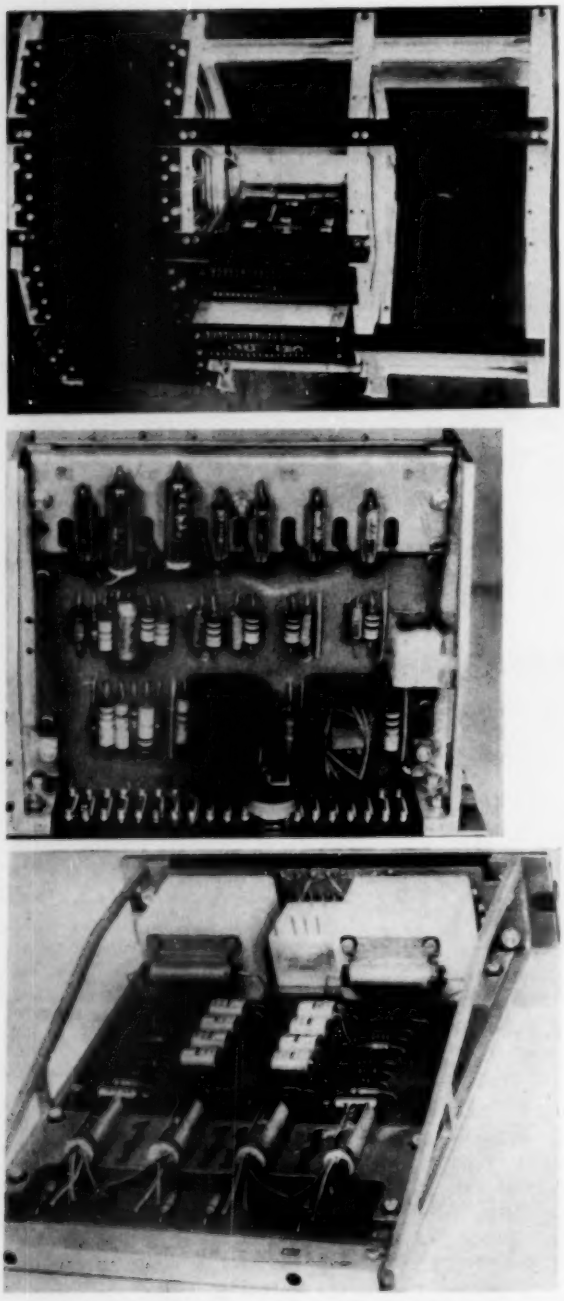

FIGURE 22. Engineered seeker—method of construction.

receiver, control electronics.)
Tested electrically.
Drop tested and monitored for disturbances.
Spot checks after drop test.

(*d*) *Complete forebody*

Overall test from artificial target simulator to wing control signals. Parts are interchangeable at (*b*), (*c*) and (*d*) levels.

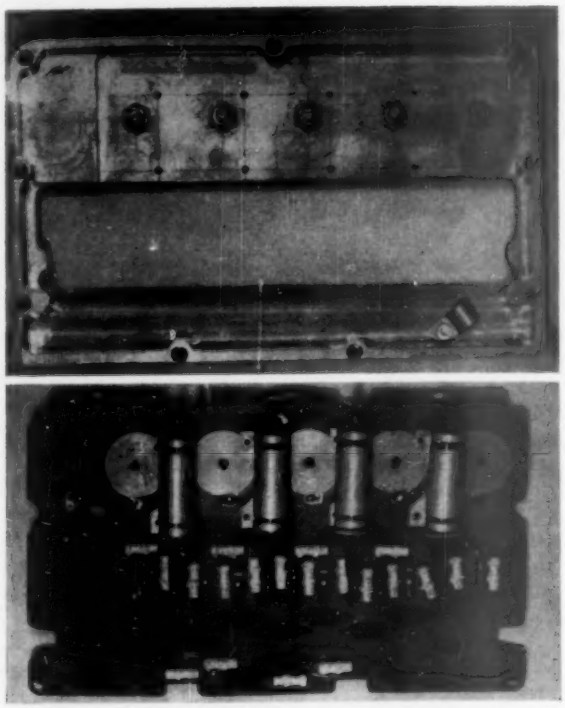

FIGURE 23. Printed circuit construction.

5. Flight Development Programme

All the foregoing techniques were explored in the course of supporting an extensive flight development programme. A fairly high rate of fire of experimental missiles has been maintained throughout the development for several reasons: —

(*a*) Considerable numbers of flights were needed for ram-jet development.
(*b*) Marginal failures would be encountered earlier and could be rectified sooner.
(*c*) The techniques for managing such a programme would make possible an easier conversion to production flow.
(*d*) Statistically significant information on some aspects of missile reliability would be obtained and reliability in initial production would be higher.

In the scale model test vehicle phase, the one quarter scale models (X.T.V.1) established some stability and drag data, and the one third scale models (X.T.V.2) executed roll and pitch manoeuvres.

The firing of the first X.T.V.4 at Aberporth from a zero length launcher marked the beginning of the full-scale flight test phase. When the tendency of these missiles to shed boost fins had been cured, the ram-jet propulsion flights were soon achieving success. The X.T.V.3 (control rounds) had started breaking up during boost, but this was soon corrected. At this time also the need for a modified tailplane and boost was appreciated, and this was introduced into both model and full-scale missiles within six months, permitting successful flight of X.T.V.5 (a ram-jet-propelled control

FIGURE 24. Bloodhound missile on launcher.

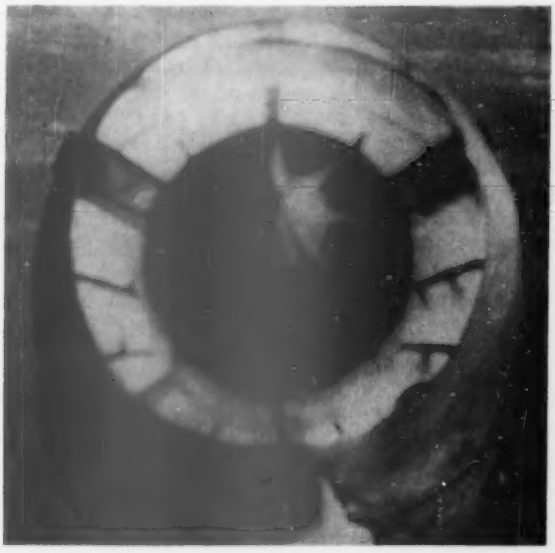

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FIGURE 25. Thor ram-jet in flight.

round). Many difficulties were encountered and overcome during the next year, and subsequently successful flights were made with a complete homing head and with a missile under manoeuvre control. At this stage the decision was taken not to begin guided flights until a homing head engineered to full weapon standard (Figs. 22 and 23) was available, and later both this and a weapon standard airframe were being flown. The subsequent development has involved successful homing flights under many different conditions. Firings and introduction into Service use began in 1958. An interception sequence from a firing is shown in Fig. 26.

6. Conclusion

There are few years of experience to draw on in guided weapon development and they provide little basis for generalisations. In this development, two factors strike one as significant.

In the first place, the engineers were given a period of unhurried study. When this was over they were encouraged to make progress at maximum rate, with as little interference as possible. These exceptionally favourable conditions helped to accelerate the project to its current trials position.

One is well aware that on occasions during the development a minor difficulty might have become a major one were it not for the convenient existence of a fortuitous and unexpected escape route. Because the designers were given sufficient freedom to follow these routes at once, on their own responsibility, much time was saved.

It is fitting to end with a reminder that the team which produces a guided weapon is one of almost unprecedented size and diversity, yet the nature of the task is such that, with Bloodhound, most members of

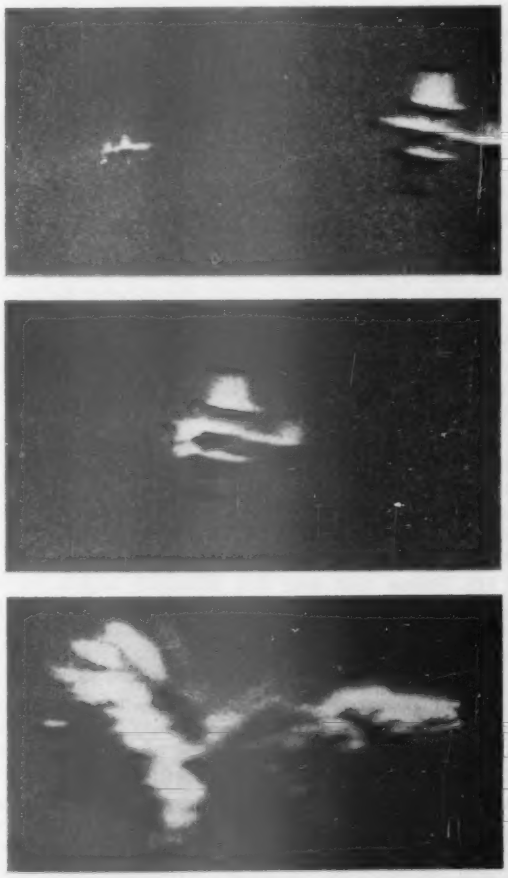

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FIGURE 26. Bloodhound interception sequence.

the development team can feel that they have made significant and essential individual contributions to the development. This is particularly true of the vigils, frustrations and achievements of the trials teams who have made a major contribution.

In concluding I would like to thank Bristol Aircraft Limited for permission to give this lecture; Messrs. Tayler, Calcraft, Metcalfe and Smith of that Company, and Mr. Best of Ferranti Limited for assistance in its compilation; and Mr. R. E. V. Hawker for assistance with illustrations.

(A short film of the Bloodhound flight trials followed.)

SUMMARY OF DISCUSSION

Mr. Pauley (Aircraft Research Association) asked whether the lecturer could expand further on his remark that the drop testing of electronic components was less destructive than resonance testing.

Mr. Farrar replied that this was his personal opinion and he felt that drop testing involved using a large amount of power for a short time, which excited all the available modes and well represented the rapid change from steady conditions to acceleration during launching. With vibration testing, it was difficult to achieve vibration levels which were representative of flight conditions and, in addition, fatigue failures of components were induced, especially if tests had to be repeated. They had found that, although crude, the drop testing method worked well and was more suitable and convenient for their purposes.

Professor Collar (University of Bristol) referred to Mr. Farrar's mention of wing tip divergence and asked whether there were any aeroelastic phenomena peculiar to missiles, as opposed to those which were simply extensions of phenomena already experienced in existing fields.

Mr. Farrar said that the differences were those of degree rather than type, and he mentioned the interaction between aeroelasticity and control systems; for missiles the control loop was a fast acting one, whereas with aircraft the control was of the auto-pilot type and comparatively sluggish in action. Another difference was that the missile engineer was able to sail much closer to the wind as regards aeroelastic effects because no human life was involved.

Professor Pearson (Royal Military College of Science) referred to the use of moving wings as opposed to fixed, Cartesian ones and asked whether it was possible to use fixed wings in combination with ram-jets, because the large body incidences involved might result in "discomfort" of the ram-jet intakes.

Mr. Farrar said that this depended largely on the application, and that this arrangement was suitable for anti-aircraft missiles, where the ram-jet intake requirements could be satisfied. He pointed out that the American Bomarc missile had fixed wings and was ram-jet propelled.

Mr. Lightbody (Sir W. G. Armstrong-Whitworth Aircraft) asked about the relative merits of wrap-round and tandem boost installations, saying that he thought that only the tandem arrangement was used in the States.

Mr. Farrar said that the wrap-round arrangement was the more compact if volumetric problems were involved, but if cross-sectional area was important, such as in going through hatches, then the tandem arrangement was better. The tandem arrangement produced more weight at the back and the stability question was therefore more of a problem. If a large wing had to be carried in front, this meant more fin at the back, and if the wings were large already then the fin size became excessive. If the wings were positioned behind anyway, then wrap-round boost was more suitable and larger wings would have a favourable effect. With the Bloodhound, the flexing problem between body and boost was a serious one and they had found that the overlap gave a stiffer joint between missile and boost. Summing up, every case had to be considered on its merits, but wing size was one of the important factors in making a choice.

Mr. Cooper (D. Napier and Son Ltd., Luton) asked whether, if Mr. Farrar had his time over again, he would prefer to work by using adequate safety factors rather than testing to destruction? Missile engineering was the first chance that people had had to press flight testing to the limit of destruction and it would be interesting to know what advantages this method held.

Mr. Farrar said that he thought there was no answer to this question. He had been satisfied with the method of approach they had used, *i.e.* going for initial weakness. The cost of making mistakes was lower and the design team were able to build up valuable experience. He thought that it was better to have the weakness in the earlier stages than to go too near the bone later.

A speaker had pointed out, with reference to the film, the tendency of audiences to laugh at pictures of missile failures and **Dr. Searby** (Ferranti Ltd.) suggested that it was only after success had been achieved that the films seemed laughable.

Mr. Watkins (Imperial College) asked whether the lecturer had had to consider the difficulty of radar interference when launching more than one missile at the same time.

Mr. Farrar said that this was certainly a question that had to be borne in mind but that no further comment was possible.

Mr. Masefield paid tribute to the lecturer for the admirable way in which he had dealt with the complex problems of the project and to his administrative ability, particularly in the way he put over his requirements. He paid tribute also to Ferranti's and to the team work between the two firms. He thought that the development of missiles and the work of the Guided Flight Section was a good example of the Society applying past experience and knowledge to new techniques. The use of twist and steer was a modern application of the moving wing monoplane technique. He thought that in the missile field the advantage of not having to worry about facilities would help considerably to accelerate progress. He felt that missiles stood now where the Spitfire and Hurricane stood in 1936, on the threshold of a new approach to problems of the future.

The Chairman, Dr. G. W. H. Gardner, also paid tribute to the lecturer and complimented him and his team on the excellent film which had illustrated very well the whole range of missile trials—vertical take-off, levitation, collision and destruction. Dr. Gardner drew attention to the large number of visitors' tickets which had been issued and said that, because of seating limitations, over a hundred more visitors had been unable to obtain tickets. Visitors were most welcome to the Society's lectures, but he hoped that many of those who had come as visitors would soon feel encouraged to apply for membership of the Society.

The Application of Automatic Digital Computers to Aeronautics*

by

S. H. HOLLINGDALE
(Royal Aircraft Establishment)

THE LAST occasion on which a lecture was given to the Society on the subject of digital computing was in 1954, when Dr. Goodwin, of the Mathematics Division, N.P.L., spoke on "The uses of the ACE Pilot Model Computer." At that time there were very few electronic digital computers in regular operation in this country and only one was primarily engaged on aeronautical work.

How far have we travelled since then? Fig. 1 gives a time chart of the main events of the 13 years from 1944, when the first automatic computer started to do useful work, to 1957. This machine, the Automatic Sequence Controlled Calculator, was the joint creation of Professor Aiken of Harvard and the International Business Machines Corporation. The founding father was, of course, Charles Babbage, who put forward proposals for the construction of an Analytical Engine in 1832. The automatic computer was, in fact, conceived in that year at Cambridge, England; it was born in Cambridge, Massachusetts, 112 years later.

The Harvard machine was electro-mechanical in operation. The first electronic digital computer, the famous ENIAC, followed very soon after and was completed in Philadelphia in 1946. British activity began in the following year; the main centres of activity during the pioneer years up to 1951, were the Universities of Cambridge, Manchester and London, and the National Physical Laboratory.

Figure 1 also includes an estimate of the number of electronic digital computers actually in operation in this country over the period. The rate of growth is more or less exponential, and we may expect to reach the 100 mark by the end of 1958. The present figure is about 50, of which 15—about 30 per cent of the total —are engaged primarily on aeronautical work. The Air side of the Ministry of Supply has five machines; two DEUCEs at Farnborough (seen in Fig. 2) and three HECs, a rather smaller machine, at Boscombe, Bedford and London. There is another HEC at the A.R.A., Bedford, and nine machines—three DEUCEs, one Ferranti Mk. 1, three Pegasus and two I.B.M. 650 Computers—in aircraft and engine firms. A number of other firms have computers on order and should be getting them during the next year or two.

In this country electronic computers have been applied to aeronautical calculations only during the past seven years. For the first half of this period the bulk of such work was done on the ACE Pilot Model at the N.P.L. The Aircraft Industry was quick to realise the value of the new tool, and more automatic computing has been done, and paid for, for the Aircraft Industry than for all other industrial users put together.

The problems of most aircraft firms are much the same, but it was found that similar problems were being formulated in different ways: this led to duplication of programming effort, delay and extra cost. To meet this situation, the S.B.A.C. set up in 1952 an Electronic Computer Panel whose major function was to standardise the arrangement of problems for digital computation. The Panel naturally turned its attention in the first place to problems that involved extensive computing and occurred frequently during aircraft design. The Panel has produced a series of documents known as Standard Forms, each of which sets out an agreed presentation of a problem in a form suitable for programming for an automatic computer. Ten Standard Forms have been issued so far, several others are in process of preparation and the S.B.A.C. has extended the scope of this admirable co-operative enterprise by setting up two further Panels to deal with engine and data processing matters. A review of the problems already dealt with indicates where the

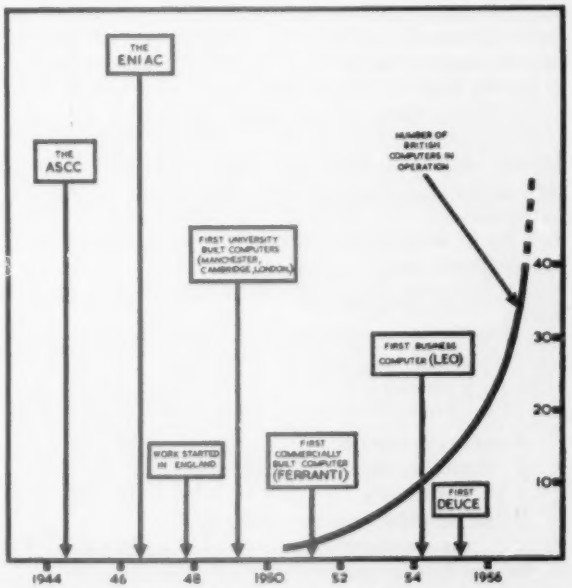

FIGURE 1. Computer time chart.

*Based on a Section Lecture given to the Society on 21st March 1957.

computational shoe pinches the aircraft designer most sharply.

The ten Standard Forms, in chronological order, cover:—

1. The normal mode problem.
2. The evaluation of flutter coefficients by strip theory.
3. The solution of the flutter problem.
4. Influence coefficients for a simple beam (engineer's theory)
5. Calculation of the resonant frequencies of a helicopter rotor blade.
6. Computation of aerodynamic forces and flutter coefficients by the Falkner-Jones theory.
7. Computation of flutter coefficients using the Multhopp-Garner theory in the compressible case.
8. The static aeroelastic problem.
9. Computation of lift and moment distributions and generalised forces for low frequency parameter supersonic flutter problems.
10. The evaluation of the wave drag of slender bodies of revolution by Dickson-Jones method.

On reading these documents one is struck by two things. First, by the central position occupied by the flutter problem. No less than eight of the ten Standard Forms are concerned either with the solution of the flutter equations themselves or with the evaluation of the various aerodynamic and structural coefficients and derivatives which enter into the flutter equations. Secondly, that in every case the problem is formulated as a series of matrix manipulations, as a problem in what is called "linear algebra." Included within this category are not only such processes as the multiplication or inversion of matrices, but also the solution of sets of simultaneous linear equations and the evaluation of the latent roots and vectors of a matrix. This concentration on linear algebra is partly due to the fact that automatic computers are particularly well suited to highly systematic and repetitive calculations, and partly because linear equations are so much more convenient to handle than non-linear ones.

It follows, then, that for aeronautical work we need a comprehensive library of Standard Programmes for dealing with the main processes of linear algebra. Now many problems involve long strings of matrix manipulations. For instance, the first S.B.A.C. Standard Form, which deals with the normal mode problem, is formulated thus.

To compute the latent roots and vectors of the matrix

$$(I - BCB'D)\,AD$$

where $C=(B'DB)^{-1}$ and:—

		Typical size of matrix
I	the unit matrix	30×30
A	flexibility matrix of influence coefficients	30×30
B	rectangular matrix defining the geometry	30×4
D	the inertia matrix, often diagonal	30×30

FIGURE 2. Two DEUCE computers at Farnborough.

Clearly what is needed in such cases is some way of simplifying the programming of sequence of matrix operations. Several interpretive schemes for doing this have been developed, the general idea being to be able to use a single order to instruct the machine to carry out a complex matrix operation, such as multiplication, which may involve many hundreds of separate arithmetical steps.

One of the interpretive schemes used on DEUCE may be taken as an illustration. The raw material consists first of a library of Standard Programmes, called bricks, and secondly of an interpretive programme, which is prepared once and for all. A brick is any DEUCE programme which is constructed so as to obey certain simple rules. The purpose of these rules is to ensure that the bricks can be obeyed one after the other under the control of the interpretive programme. This programme reads and stores on the magnetic drum a number of such bricks and then causes them to be obeyed in a manner specified by a series of code words.

Each code word is a 32 binary digit number, the standard word length in DEUCE, which is interpreted as four 8-digit numbers, a, b, c and d. A code word instructs the machine to do two things, to obey one of the bricks, specified by the number d, and to provide that brick with up to 3 parameters, a, b and c, which specify where the data is to be found and what is to be done with the results.

Let us consider a simple example: the evaluation of a set of matrices of the form $A_r+\lambda B_r'$, $(r=1, 2 \ldots n)$, the matrices A_r and B_r and the scaler λ being given. The procedure is to assemble a pack of punched cards* made up as follows:—

(*a*) The interpretive programme.
(*b*) A card specifying the number of "bricks" to be read in.
(*c*) The standard bricks required for the problem:
  (1) Read matrix
  (2) Transpose
  (3) Read scalar
  (4) Multiplication by scalar

*DEUCE uses Hollerith cards for both input and output.

(5) Matrix addition
(6) Punch out matrix

(*d*) Three cards containing the code words.

(*e*) The various matrices and scalars forming the data:
B_1, λ_1, A_1; B_2, λ_2, A_2; and so on.

The interpretive programme is first read in and is then told to read a number of bricks, in this case six, and to store them on the drum. The code words are read in next and decoded and obeyed by the interpretive programme. Our problem needs eight code words, numbers 0 to 7, the action of each code word being as follows:—

Code word Number	*Action*	*Result*
0	Obey brick No. 1. Read in matrix B and store in location c.	B
1	Obey brick No. 2. Form transpose of matrix in location a; store result in location c.	B'
2	Obey brick No. 3. Read scalar.	λ
3	Obey brick No. 4. Multiply matrix in location a by scalar; store result in location c.	$\lambda B'$
4	Obey brick No. 1. Read in matrix A and store in location c.	A
5	Obey brick No. 5. Add matrix in location a to matrix in location b; store result in location c.	$A+\lambda B'$
6	Obey brick No. 6. Punch out matrix in location a.	
7	Go back to code word No. "0"	

a, b and c may have different values in different code words; *e.g.* c (code word 0) = a (code word 1).

It must be understood that the phrase "stored in location c" means that the elements of the matrix are stored in consecutive locations on the drum with the first element in location c. Each matrix is preceded by a parameter card in which is specified the number of rows and columns of the matrix, the position of the binary point in the elements, and a scale factor for checking purposes.

TABLE I

Class of Work	*Total Hours*	*Per Cent of Total*	*Hours per week*
Programme Testing	1017	30·7	13·4
Armament and Weapon Calculations	1454	44·0	19·1
Flutter and Normal Modes	58		
Analysis of Fatigue and Gust Data	33		
Miscellaneous Structural Calculations	14		
Aerodynamic Derivatives	67		
Wave Drag Calculations	40		
Other Aerodynamic and Performance Calculations	102		
Wind Tunnel Design	73	16·4	7·1
Reduction of Wind Tunnel Data	60		
Machining of Wind Tunnel Models	19		
Other Miscellaneous Items	75		
Programme Library	22		
Research	82	8·9	3·9
Training, Demonstrations, etc.	190		
Total "Good Time"	3306	100	43·5

The only programming needed for this particular problem is to write out the eight code words, and it will be apparent that the use of an interpretive scheme of this kind, supported by an adequate library of bricks (there are more than 100 for DEUCE), cuts out most of the drudgery and saves most of the time of programming linear algebra calculations.

Turning now from the Aircraft Industry to the research establishments, it will be convenient, in the interests of brevity, to confine attention to the largest

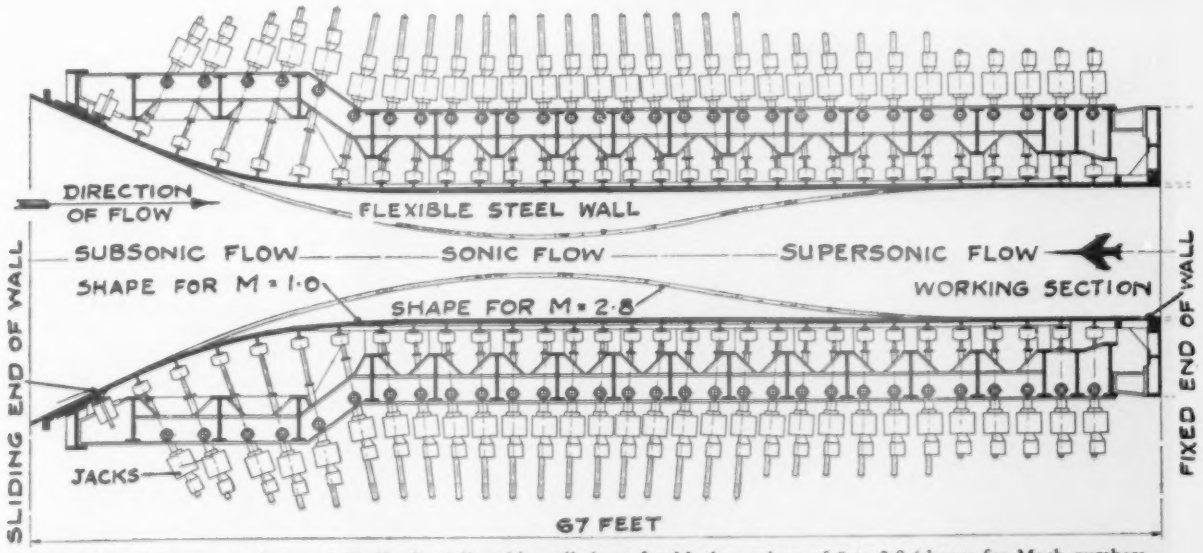

FIGURE 3. 8 ft. supersonic tunnel (Bedford). Adjustable wall shape for Mach numbers of 0 to 2·8 (shapes for Mach numbers of 1·0 and 2·8 shown).

of these, the R.A.E. The first of the two DEUCE computers was installed at R.A.E. in June 1955; the second in December 1956 (*see* Fig. 2). Up to the end of February 1957 (a period of 76 machine weeks) a total of 3,300 hours of "good computing time" had been achieved; an average of 43½ hours per machine-week. Another 10 hours per week, on the average, is devoted to the routine checking and servicing of each machine. A summary of the utilisation of the R.A.E. DEUCE computers from August 1955 to February 1957 is shown in Table I.

Much of the work referred to as "armament and weapon calculations" consists of the step-by-step solution of sets of ordinary differential equations, usually non-linear, while a substantial part of the remainder consists of linear algebra.

The rôle of an automatic computer in aeronautical research may be illustrated by considering a particular example: the aerodynamic design and control of the 8 ft. × 8 ft. wind tunnel at R.A.E., Bedford, which has an operating range from $M=0$ to $M=2{\cdot}8$. Now since the air speed in the working section of a supersonic tunnel depends on the shape of the walls upstream, it is necessary, in order to change the operating Mach number, to alter the wall shape—by adding liner blocks, for instance. To avoid this cumbersome procedure, a new method was adopted in this case. The tunnel is two-dimensional and the upper and lower walls of the adjustable part consist of two flexible steel plates 60 ft. long, 8 ft. wide and 1 in. thick. The shape of each plate can be varied continuously and automatically by means of 30 pairs of screw jacks, the movement of each jack being controlled by a length of punched tape. The walls are fixed at the supersonic end, but can slide with constant slope at the subsonic end, as indicated in Fig. 3. The computational problem was to evaluate the wall shapes for the range of operating speeds, then to calculate the required jack movements, and finally to prepare the set of control tapes. In the conventional

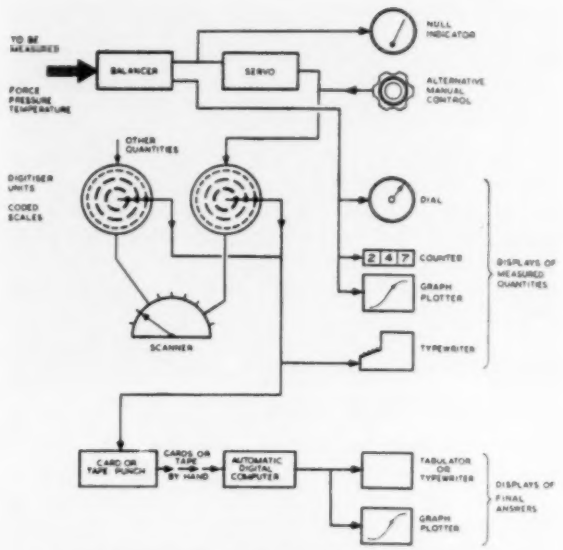

FIGURE 4. Automatic wind tunnel recording equipment.

method of tunnel design different mathematical techniques are used to deal with the subsonic, transonic and supersonic regions, this piecemeal approach being indicated by the fact that the governing differential equations are of elliptic type when the flow is subsonic, and of hyperbolic type when it is supersonic.

Preliminary investigations showed that sufficient continuity across the boundaries of the separate regions could not be achieved in practice by conventional methods; what was wanted was a unified treatment of the problem over the whole length of the tunnel and the complete range of Mach number. Now the need for a different mathematical approach in the subsonic and supersonic regions is in fact governed by the way in which the boundary conditions are specified. Normally one works from an assumed wall shape and calculates the flow. If, on the other hand, one regards the wall shape as entirely unknown, but starts from an assumed flow velocity vector along one boundary, then it can be shown that the complete range of Mach number can be dealt with without introducing singularities. This was the approach adopted in this instance, and the boundary chosen was, naturally enough, the centre line of the tunnel, the line of symmetry in the two-dimensional flow field.

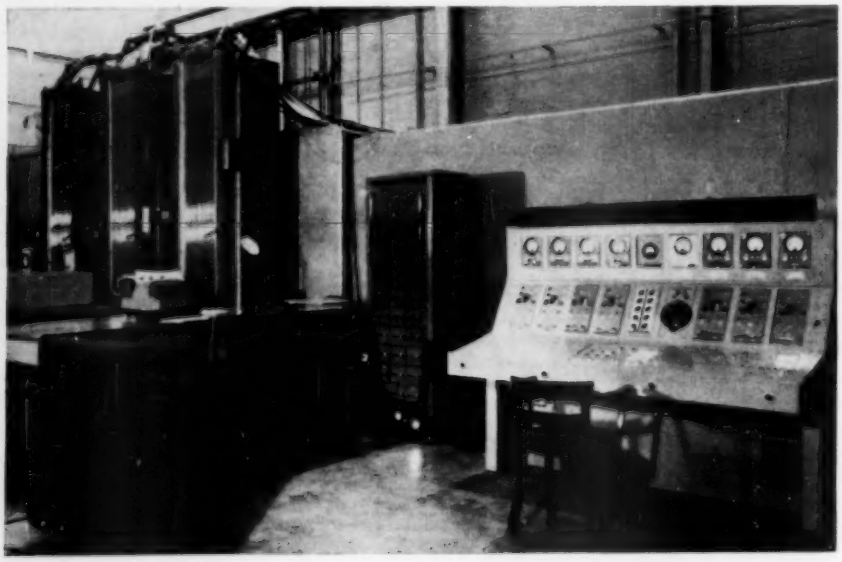

FIGURE 5. General view of an early wind tunnel installation.

The first stage, then, was to construct an arbitrary formula giving velocity distributions along the centre line for various operating speeds. These distributions must be chosen to satisfy the physical and engineering conditions of the problem, and a certain amount of trial and error adjustment had to be done as the work proceeded. The flow field is then calculated step-by-step by working out from the centre line.

It is convenient to transform the equations of flow to express the velocity vector (q, θ) in terms of a potential function, ϕ, and a stream function, ψ. Writing $s=q/a_c$, where a_c is the velocity of sound at the throat, the flow can be expressed in non-dimensional form by the two linear partial differential equations

$$\frac{\partial s}{\partial \psi} = F_1(s)\frac{\partial \theta}{\partial \phi}$$

and

$$\frac{\partial \theta}{\partial \psi} = F_2(s)\frac{\partial s}{\partial \phi} \ ,$$

where s and θ are known as functions of ϕ along the centre line $\psi=0$. These equations may be regarded as the inverse of the Hodograph equations; dependent and independent variables being interchanged.

The flow field at the mesh point of a grid of streamlines and equipotentials can then be calculated. The procedure is to differentiate s and θ numerically with respect to ϕ and so get the gradients normal to a streamline, and then to integrate numerically with respect to ψ to give (s, θ) along a new streamline. The process is repeated, working out to a new streamline each time, until the whole field is defined. Nine equal steps of ψ were taken, so that ψ_9 was the wall. The values of ϕ were chosen, not at equal intervals, but so that successive equipotential lines intersect the centre line at uniform intervals. The whole process was repeated for twelve Mach numbers in the range.

The next step was to express the wall shape in terms of Cartesian co-ordinates, values of (x, y) being obtained by integration for each intersection of the computed equipotential lines with the wall. From time to time during these calculations the curvature along the whole length of the wall was checked to see that it did not exceed the permissible engineering limits. The lengths along the wall of the various intersection points were next calculated by integration from the fixed down stream end. Now each jack is hinged at a fixed point whose co-ordinates are known; the moveable end is attached to the wall by a pin joint. The co-ordinates of each jack attachment point, and hence the extension of each jack, can thus be computed by inverse and direct interpolation for each of the calculated wall shapes.

FIGURE 6. Semi-automatic instrument for reading continuous trace records.

The next stage was to subtabulate the jack extensions to such small intervals of Mach number that no jack ever moves more than one unit in going from one Mach number to the next. The "unit" jack movement specified by the tunnel designers was either 1/400 in. or 1/800 in. depending on the position along the wall. To meet this condition, about 18,000 steps of Mach number had to be taken. The subtabulation was done in two stages, the interval in the second stage being reduced by a factor of 256, a convenient number for a binary computer. The actual jack extensions at each step were not recorded, but only their first differences. Any such difference must be $+1$, 0 or -1; any jack can only increase or decrease in length by one unit, or not change at all, at each step. These differences were computed on DEUCE, punched on Hollerith cards and finally transferred to the punched tapes used to control the jacks.

One other tape had to be prepared, a master tape calibrated in equal intervals of Mach number. This tape is used to control the separate jack tapes so as to

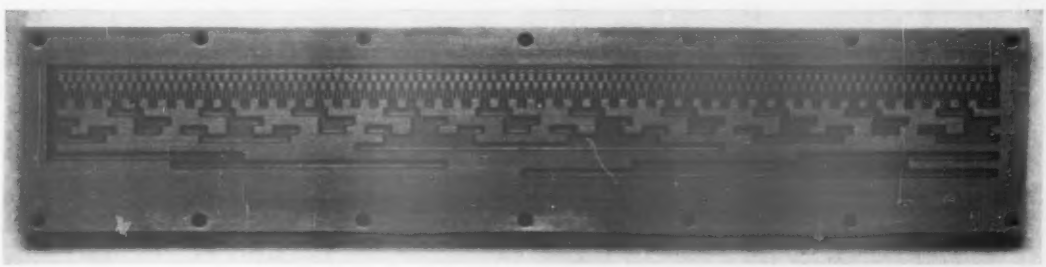

FIGURE 7. Linear coded scale.

set all the jacks simultaneously to a specified Mach number.

The whole job, which was spread over several years, consumed over 150 electronic computer hours and also entailed a good deal of desk calculation. The early part of the work was done on the ACE Pilot Model at the N.P.L., the later part on the DEUCE at R.A.E.

Two other fields of computer application may be mentioned briefly in conclusion. The first of these is the processing of experimental data. Aeronautical research and development generates vast quantities of experimental records, from continuous traces on rolls of paper to ciné photographs of instrument dials or of missiles in flight. The actual computation involved in this class of work is usually fairly straightforward, sometimes quite trivial, but it is often worthwhile doing on an automatic computer because there is such a lot of it. To achieve the full benefits of high speed computing, we must mechanise not only the computing itself, but also the process of converting the experimental data into a form in which it can be fed to the machine. Considerable effort, both in the research establishments and in industry, is being devoted to this problem, and Fig. 4 gives a schematic chart of the wind tunnel instrumentation scheme that has been adopted at Farnborough and Bedford. Its essential feature is the automatic production, on the tunnel site, firstly of packs of Hollerith cards for processing on DEUCE, and secondly, of a typewritten or graphical display of the unreduced data to guide the tunnel operators during the progress of the experiment.

Figure 5 gives a general view of an early wind tunnel installation; it shows the console with the null indicators and the counters displaying the measured quantities, the cabinet containing the scanning and digitising equipment, the typewriter and the Hollerith punch. The working section of the tunnel is just off the picture to the right.

Figure 6 shows a semi-automatic instrument developed at R.A.E. for reading continuous trace records. Once again, the output consists of punched cards and a typewritten record, both being produced automatically when the operator presses a foot switch.

In most devices of this kind, measured quantities must be converted to digital form as a train of electrical pulses. Fig. 7 shows a linear coded scale used for this purpose in the trace reader, while Fig. 8 shows a circular scale used with wind tunnel strain gauge balances for digitising a shaft rotation.

FIGURE 8. Circular coded scale.

The second field is the use of digital computers to control metal cutting operations. The function of the computer here is to provide continuous instructions to a machine tool on the paths the cutter must follow in order to produce the desired article. This has obvious applications to the Aircraft Industry where many different components are required, each in fairly small quantities, but to very high precision. In the research and development field there is the problem of machining from the solid aerodynamic models for supersonic tunnel tests. Work in this field is still in its infancy, and it seems likely that the main difficulties will prove to be of an engineering rather than a computational nature. However, the potential saving, both of time and skilled labour, are so substantial that a determined and sustained attack on the problem may be expected during the next few years.

TECHNICAL NOTES

Tensile Strut-Testing Machines

A. H. CHILVER, M.A., Ph.D., A.F.R.Ae.S.
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IN A RECENT NOTE[1], Fessler has suggested that some of the practical problems of strut testing can be overcome by using a "tensile strut-testing machine". As Fessler points out, slender struts are frequently tested with pinned ends, either in the form of knife-edges or ball-ends. Fessler then goes on to state that

> " . . . In conventional testing machines this results in a compression column with two pin joints. The instability of this column makes the accurate alignment of the loading members important, and reliable testing becomes correspondingly difficult".

For a strut with knife-edge ends (or ball-ends of very small radius) instability of the strut has little or no effect on the testing machine. This is so because a member with knife-edge ends can be loaded through only two points, *i.e.* along the knife-edges, and for the body to be in a condition of statical equilibrium the forces at these points must be equal and opposite. The forces on a strut with knife-edge ends then reduce to two forces of equal magnitude and mutually opposed; these forces are directed along the line joining the two knife-edges. This is equally true of the strut in any buckled condition, since the external loads on the strut are still being applied through the knife-edges. It follows that instability, or the development of a buckled form, has little or no effect on the behaviour of the testing machine, when the strut is loaded through knife-edges. In the buckled condition of the strut, the only effect external to the strut is a reduction of compressional stiffness of the strut.

For a similar reason highly accurate alignment of a knife-edge strut in a testing machine is not important, provided the eccentricities developed do not impair the efficiency of the load-measuring device of the machine. Lateral deflections of the strut should always be measured relative to the line joining the knife-edges.

An important problem in the testing of struts with knife-edge ends is that the testing machine may itself become unstable independently of the strut. A simple study of this problem has been made in Ref. 2; an important conclusion is that where a compression test specimen is shorter than the ties connecting the head of the machine to the base, there is usually the possibility of buckling of the testing machine itself. Fig. 1(*a*) shows a schematic arrangement of a compression test specimen, loaded between the rigid cross-members of a testing machine. The cross-members are connected by relatively flexible ties, which are built into the lower cross-member and pinned to the upper cross-member.

At some critical value of the compressive load in the strut, the whole machine becomes unstable, and lateral movements of the upper cross-member occur; this critical load is dependent only on the stiffnesses of the ties, and not on the stiffness of the strut under test. In practice, the critical load is usually considerably greater than the normal working load of the machine; but initial imperfections in the ties of the machine may lead to distortions at relatively low working loads.

In the arrangement of Fig. 1(*a*) the strut under test is shorter than the ties connecting the cross-members. If the relatively rigid cross-members can be arranged, as in Fig. 1(*b*), so that the ties are slightly shorter than the strut under test, then the arrangement is stable for all loads in the strut.

Provided the loads applied to the strut can be measured accurately, distortions of the testing machine have no effect on the behaviour of a strut with knife-edge ends. The main difficulty is that testing machine instability usually impairs the efficiency of the load-measuring device of the machine, and large distortions are to be avoided as far as possible.

The arrangement proposed by Fessler avoids instability problems in the frame of the loading rig; but, if this frame must itself be loaded in a tensile testing machine, for large loads instability problems may arise in the tensile machine. This problem is also discussed in Ref. 2.

In Fessler's frame the frictional forces at the joints should be as small as possible; for large loads and long struts, there may be difficult problems in designing suitable joints. In assessing the importance of friction in Fessler's frame, the author does not agree completely with the analysis given by Fessler. The four tensile members forming the frame are shown in Fig. 2; forces P applied at joints B and D are resisted by forces R on the strut, which is placed between joints A and C. Consider in particular the member CD; the forces on this member are shown more fully in Fig. 3; C and D define the centres of the pins at the ends of the member. In practice, pins or ball-bearings will be used in the joints at C and D; suppose for simplicity that the loads at C are transmitted through three small balls, 1, 2, 3, of negligible radius; ball 1 at C is on the line DC extended, and balls 2 and 3 at C lie on a line perpendicular to DC and passing through C. Similarly, the loads at D are taken through three small balls, 1, 2, 3; each set of balls lies on a circle of radius r. Suppose the load on ball 1 at C is Q along the direction

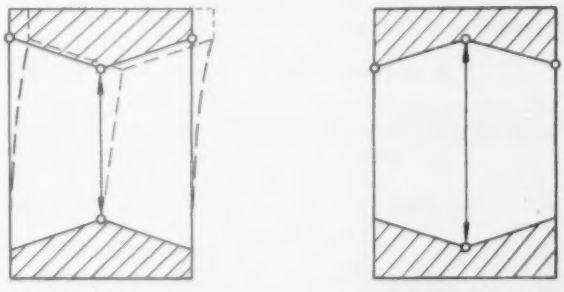

FIGURE 1. (*a*) Potentially unstable arrangement. (*b*) Stable arrangement at all loads.

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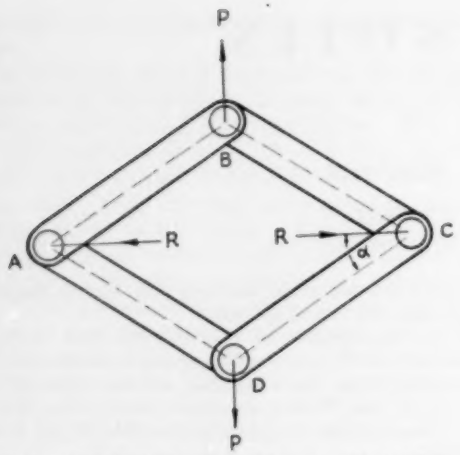

FIGURE 2. Arrangement of members in Fessler's "tensile" frame.

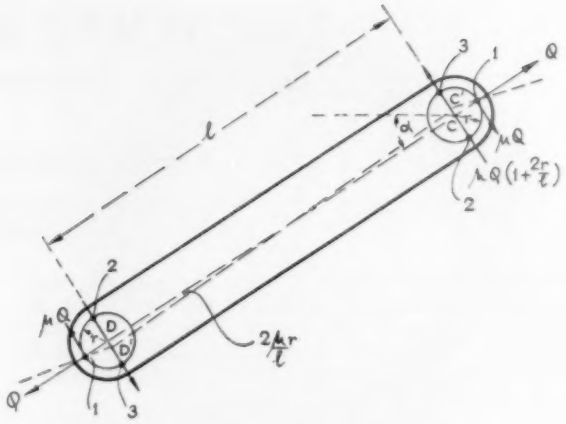

FIGURE 3. Loads in the member CD.

DC. Then if the framework is in the process of unfolding (*i.e.* if the distance BD in Fig. 2 is increasing) there is a frictional force μQ on ball 1 at C. This frictional force μQ will be small compared with Q, and the radial forces on balls 2 and 3 at C will be of order μQ; we may therefore neglect any tangential frictional forces on balls 2 and 3 at C. In this case, the radial and tangential forces on ball 1 at D are also Q and μQ, respectively. We find finally that small equal and opposite forces

$$\mu Q\left(1+\frac{2r}{l}\right) \quad . \quad . \quad . \quad (1)$$

are set up at C and D on lines through balls 2 and 3. Now the resultant of all forces at the end C of the member passes through the point C', where $CC'=\mu r$. Similarly, at the end D, the resultant of all forces passes through D', where $DD'=\mu r$. Then $C'D'$ is the line of action of the resultant tensile force in the member CD; $C'D'$ is inclined to CD by a small angle

$$\frac{2\mu r}{l}, \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and the angle between $C'D'$ and the force R in the strut is therefore

$$\alpha+\frac{2\mu r}{l}. \quad . \quad . \quad . \quad . \quad (3)$$

The line $C'D'$ is the "effective" position of the member CD, and we may consider truly frictionless pins to exist at C' and D'. Then the force R in the strut in terms of P applied to the frame is

$$R=P\cot\left(\alpha+\frac{2\mu r}{l}\right) \quad . \quad . \quad . \quad . \quad (4)$$

If $(2\mu r/l)$ is small, we have approximately

$$R=P\cot\alpha\left[\frac{1-\frac{2\mu r}{l}\tan\alpha}{1+\frac{2\mu r}{l}\cot\alpha}\right]. \quad . \quad . \quad . \quad . \quad (5)$$

When μ approaches zero,

$$R=P\cot\alpha, \quad . \quad . \quad . \quad (6)$$

which is the value of R for frictionless pins. Equation (6) also defines the value of R when r, the radius of the pins, approaches zero; this is so because for pins of negligible radius the members are effectively connected to each other through knife-edges, for which there are no frictional effects.

Fessler, on taking account of friction, gives the relation

$$R=P\cot\alpha\left[\frac{1-\mu\left(1+\frac{2r}{l}\right)\operatorname{cosec}2\alpha}{1+\mu\left(1+\frac{2r}{l}\right)\operatorname{cosec}2\alpha}\right]. \quad . \quad . \quad (7)$$

When μ approaches zero, this reduces to equation (6). But when r approaches zero, equation (7) reduces to

$$R=P\cot\alpha\left[\frac{1-\mu\operatorname{cosec}2\alpha}{1+\mu\operatorname{cosec}2\alpha}\right]. \quad . \quad . \quad (8)$$

This suggests, in contradiction to equation (6), that frictional effects are important, even when the pins are negligibly small; it is not immediately clear why equation (8) should include μ; however, this may be completely explicable if the forces shown in Fig. 2 of Fessler's note can be justified.

Fessler suggests that the load R applied to the strut between A and C (Fig. 2) should be estimated by first measuring the distance $2y$ between B and D, and then deducing R from the relation

$$R=P\left[\left(\frac{l}{y}\right)^2-1\right]^{\frac{1}{2}}. \quad . \quad . \quad (9)$$

Suppose there are small errors $\pm\delta P$ and $\pm\delta y$ in the measured values of P and y, respectively. Then the fractional error in R is

$$\frac{\delta R}{R}=\pm\frac{\delta P}{P}\pm\left(\frac{l^2}{l^2-y^2}\right)\frac{\delta y}{y}. \quad . \quad . \quad (10)$$

If the fractional errors in P and y are of the same order, then the error in R is of the order

$$\frac{\delta R}{R}=\left[\pm1\pm\frac{l^2}{l^2-y^2}\right]\frac{\delta y}{y}. \quad . \quad . \quad (11)$$

Suppose, as a particular example, that $l=2y$ (or $\alpha=30°$), then

$$\frac{\delta R}{R}=\left(\pm1\pm\frac{4}{3}\right)\frac{\delta y}{y}=\pm\frac{7}{3}\frac{\delta y}{y}. \quad . \quad (12)$$

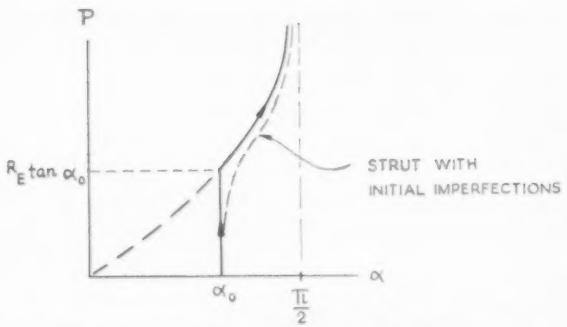

FIGURE 4. Loading of the frame after buckling of the strut.

Again, if $l\sqrt{3}=2y$, (or $\alpha=60°$), then

$$\frac{\delta R}{R}=(\pm 1 \pm 4)\frac{\delta y}{y}=\pm 5\frac{\delta y}{y}. \quad . \quad . \quad (13)$$

Clearly, as α increases the errors in measuring load in the strut may be considerably greater than those in the measurement of the distance between points B and D.

One further interesting feature of Fessler's arrangement is that the frame is in a condition of stable equilibrium after the onset of elastic buckling of the strut. Imagine that the strut placed between joints A and C is perfectly straight and axially loaded; suppose R_E is the Euler load of the strut, and that after the onset of buckling, the strut itself is in a condition of neutral equilibrium, the end load R_E on the strut remaining constant for any small amount of shortening between the ends of the strut. Then after the onset of buckling of the strut in the frame of Fig. 2 we have

$$R=R_E=P\cot\alpha. \quad . \quad . \quad . \quad (14)$$

Then

$$P=R_E\tan\alpha. \quad . \quad . \quad . \quad (15)$$

For a strut of negligible axial compressibility, there is no change of geometry of the frame until the thrust in the strut attains the critical value R_E. If α has initially the value α_0 (Fig. 4), then the critical condition is reached when

$$P=R_E\tan\alpha_0. \quad . \quad . \quad . \quad (16)$$

As the strut shortens under a constant load, R_E, the tensile load P on the frame increases as the angle α increases. For a perfect strut there is a sharp discontinuity in the $P-\alpha$ curve of Fig. 4 when the strut buckles; for an initially imperfect strut, the angle α would increase from the onset of loading, and the interpretation of the $P-\alpha$ diagram would prove more difficult, since there is then no discontinuity in the $P-\alpha$ relation.

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A Simplified Numerical Analysis

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LIAISON BETWEEN the engineering and computing sections of an aircraft company suffers when the engineer feels he is "losing control" of his own problems. This situation is typically due, not to distrust of the calculating engine, but to variance in the numerical methods favoured by the engineer and the engine programmer.

A way of meeting this situation is to develop the familiar determinantal notation into a calculus amenable both to human and to engine computation. Three years of experience with this *lingua franca* by engineers and programmers of one company has proved satisfactory, demonstrating its great flexibility and power. Many of the better, older methods can be derived from this calculus, as well as many new methods.

The primary development is through a determinantal geometry of high mnemonic value. This is then reduced to matrix form. The discussion is limited to the elemental operations of analysis in a 2-space, but the extensions will be obvious.

THE IMPLICIT SCALAR APPROXIMATOR

The basic problem of numerical analysis is the construction of a linear or polynomial approximator to a function that is non-linear, non-algebraic or tabulated, in some neighbourhood of the function. This is because linear and polynomial functions are those most easily handled.

An implicit linear approximator to the scalar function $f(x, y)$ in some neighbourhood of (x_i, y_i) uses the familiar geometric determinant

$$\Phi(f, x, y, 1)_i=\begin{vmatrix} f & x & y & 1 \\ f_i & x_i & y_i & 1 \\ f_{i-1} & x_{i-1} & y_{i-1} & 1 \\ f_{i-2} & x_{i-2} & y_{i-2} & 1 \end{vmatrix} \doteq 0. \quad . \quad (1)$$

The symbol $\doteq$ ("linearly equal to") designates that the equality is that of a linear approximation. Higher order implicit approximations to $f(x, y)$ are possible, as

$$\Phi(f, x^2, xy, y^2, x, y, 1)_i \doteq 0 \quad . \quad . \quad (2)$$

THE VECTOR APPROXIMATOR

A linear approximator to the vector function

$$u=f(x, y)$$
$$v=g(x, y) \quad . \quad . \quad . \quad . \quad (3)$$

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in some neighbourhood of (x_i, y_i) is the generalised Lagrangian form

$$[u\ v] \doteq [x\ y\ 1]\begin{bmatrix} x_i & y_i & 1 \\ x_{i-1} & y_{i-1} & 1 \\ x_{i-2} & y_{i-2} & 1 \end{bmatrix}^{-1}\begin{bmatrix} u_i & v_i \\ u_{i-1} & v_{i-1} \\ u_{i-2} & v_{i-2} \end{bmatrix}. \quad . \quad (4)$$

Let us call

$$P(x, y, 1)_i = \begin{bmatrix} x_i & y_i & 1 \\ x_{i-1} & y_{i-1} & 1 \\ x_{i-2} & y_{i-2} & 1 \end{bmatrix} \quad . \quad . \quad (5)$$

a linear "plat" ("plat" is a surveyor's term for a small plot of ground, *i.e.* neighbourhood). Higher order approximations to (3) are possible, using quadratic or higher order plats.

THE SCALAR APPROXIMATOR

Relation (1) expands to

$$f(x, y) \doteq \frac{x\phi(f, y, 1)_i + y\phi(x, f, 1)_i + \phi(x, y, f)_i}{\phi(x, y, 1)_i} \quad . \quad (6)$$

in terms of the minor determinants,

where $$\phi(x, y, 1)_i = \begin{vmatrix} x_i & y_i & 1 \\ x_{i-1} & y_{i-1} & 1 \\ x_{i-2} & y_{i-2} & 1 \end{vmatrix} \quad . \quad . \quad . \quad (7)$$

In typical applications the points cluster about (x_i, y_i), the latest and best point obtained by some iterative procedure, and the cluster grows tighter (the points converge) as the iteration progresses. For this reason we shall call $\phi(x, y, 1)_i$ a linear "cluster." It is a generalised n-dimensional form of Vandermonde's determinant.

Geometrically the linear cluster (7) is numerically equal to the product of the distance between any two of the points and the perpendicular distance of the third point from the line of these two. Obviously, a linear cluster in general is a measure of the departure of $n+1$ points from linearity in an n-space.

To obtain an analytical meaning (other than that of being the determinant of a plat), consider the general transformation (3). Expanding these functions by (6) and differentiating, an interesting result follows.

The Jacobian of the transformation (3) at (x_i, y_i) is

$$\left.\frac{\partial(u, v)}{\partial(x, y)}\right|_i \doteq \frac{\phi(u, v, 1)_i}{\phi(x, y, 1)_i} \quad . \quad . \quad . \quad (8)$$

Linear clusters are then n-dimensional variable differences of the first order, the numerical analogues of n-dimensional partial differentials of the first order. More generally, since

$$\phi(x^3, x^2, x, 1)_i = [(x_i - x_{i-1})(x_i - x_{i-2})(x_i - x_{i-3})] \times$$
$$\times [(x_{i-1} - x_{i-2})(x_{i-1} - x_{i-3})]\ [(x_{i-2} - x_{i-3})]$$

then $$\phi(x^3, x^2, x, 1)_i \doteqdot 3!!\, dx^6 \quad \phi(f, x^2, x, 1)_i \doteqdot 2!!\, d^3f dx^2 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where 3!! represents 3!2!1!

RELATION OF PLATS TO CLUSTERS

As the evaluation of determinants beyond the third order is tedious, cluster formulae must often be converted to the plat form. Looking ahead to formula (20), this may be converted to (24) by observing that

$$\begin{bmatrix} f_i & g_i & 1 \\ f_{i-1} & g_{i-1} & 1 \\ f_{i-2} & g_{i-2} & 1 \end{bmatrix}^{-1}\begin{bmatrix} x_i & y_i \\ x_{i-1} & y_{i-1} \\ x_{i-2} & y_{i-2} \end{bmatrix}$$
$$= \frac{1}{\phi(f, g, 1)_i}\begin{bmatrix} \phi(x, g, 1) & \phi(y, g, 1) \\ \phi(f, x, 1) & \phi(f, y, 1) \\ \phi(f, g, x) & \phi(f, g, y) \end{bmatrix}_i \quad . \quad (10)$$

COMPUTATIONAL TECHNIQUES

It is required to evaluate determinants of the second and third orders and to perform the matricial operation $A^{-1}B$. The process of elimination by addition and subtraction is recommended for the latter operation: —

$$\begin{bmatrix} 3 & -2 & 1 \\ -1 & 3 & 2 \\ 2 & 2 & 3 \end{bmatrix}^{-1}\begin{bmatrix} 4 & 8 \\ 15 & 23 \\ 22 & 36 \end{bmatrix} \quad .$$
$$= \begin{Vmatrix} 1 & -2/3 & 1/3 & 4/3 & 8/3 \\ 0 & -7/3 & -7/3 & -49/3 & -77/3 \\ 0 & 5/3 & 7/6 & 29/3 & 46/3 \end{Vmatrix}$$
$$= \begin{Vmatrix} 1 & 0 & 1 & 6 & 10 \\ 0 & 1 & 1 & 7 & 11 \\ 0 & 0 & -3/10 & -6/5 & -9/5 \end{Vmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 2 & 4 \\ 3 & 5 \\ 4 & 6 \end{bmatrix} = \begin{bmatrix} 2 & 4 \\ 3 & 5 \\ 4 & 6 \end{bmatrix}.$$

The typical iterative process encountered later is started with the given estimate (x_0, y_0) and a sufficient number of nearby points, as $(1.1x_0, y_0)$, $(x_0, 1.1y_0)$.

INTERPOLATION

Expansion of the corresponding geometric determinant provides formulae for interpolation, as (6), and for inverse interpolation, as

$$y \doteq \frac{u\phi(y, v, 1)_i + v\phi(u, y, 1)_i + \phi(u, v, y)_i}{\phi(u, v, 1)_i} \quad . \quad (11)$$

Sets of formulae of the type (6) or (11) may be compactly expressed in terms of plats, as (4).

If something better than linear interpolation is desired, resort may be had to quadratic, cubic, . . . or transcendental clusters or plats. Thus, interpolating formulae for $f(x)$ are

$$\left.\begin{aligned} f(x) &\doteqdot \frac{x^2\phi(f, x, 1)_i + x\phi(x^2, f, 1)_i + \phi(x^2, x, f)_i}{\phi(x^2, x, 1)_i} \\ f(x) &\doteqdot [(x - x_i)^2\ (x - x_i)]\begin{bmatrix} (x_{i-1} - x_i)^2 & (x_{i-1} - x_i) \\ (x_{i-2} - x_i)^2 & (x_{i-2} - x_i) \end{bmatrix}^{-1} \times \\ &\qquad \times \begin{bmatrix} f_{i-1} - f_i \\ f_{i-2} - f_i \end{bmatrix} + f_i \end{aligned}\right\} \quad (12)$$

DIFFERENTIATION

It follows from (8) that linear clusters are useful in computing first derivatives. Thus

$$\left.\frac{\partial u}{\partial x}\right|_i \doteq \frac{\phi(u, y, 1)_i}{\phi(x, y, 1)_i}; \quad \left.\frac{\partial v}{\partial y}\right|_i \doteq \frac{\phi(x, v, 1)_i}{\phi(x, y, 1)_i}. \quad (13)$$

If second derivatives are required, one must resort to quadratic clusters. Then, for example,

$$\left.\frac{\partial^2 u}{\partial y^2}\right|_i \doteq 2!\,\frac{\phi\,(x^2, xy, u, x, y, 1)_i}{\phi\,(x^2, xy, y^2, x, y, 1)_i}\,,$$
$$\left.\frac{\partial^2 v}{\partial x \partial y}\right|_i \doteq 2!\,\frac{\phi\,(x^2, v, y^2, x, y, 1)_i}{\phi\,(x^2, xy, y^2, x, y, 1)_i}\,. \quad . \quad . \quad (14)$$

The symbolic cancellation principle, based on (9), that will allow the user to make up formulae as desired, is now apparent.

If it is desired to use quadratic clusters to evaluate first derivatives also, it is first necessary to translate the co-ordinate system to an origin at the desired point of evaluation (as was done with the second formula of (12)), as follows: —

$$\left.\begin{aligned} X &= x - x_i \qquad U = u - u_i \\ Y &= y - y_i \qquad V = v - v_i \end{aligned}\right\} \quad . \quad . \quad (15)$$

This has to be done because n^{th} order clusters, for n greater than one, are not invariant under Euclidean transformations. Relations such as (14) still hold in this new system. In addition, the following new relations are true: —

$$\left.\frac{\partial v}{\partial y}\right|_i = \left.\frac{\partial V}{\partial Y}\right|_i \doteq \frac{\phi\,(X^2, XY, Y^2, X, V, 1)_i}{\phi\,(X^2, XY, Y^2, X, Y, 1)_i}\,. \quad (16)$$

Sets of relations of the type (13), (14) or (16) may be compactly expressed in terms of plats, as

$$\begin{bmatrix} \partial u/\partial x_i & \partial v/\partial x_i \\ \partial u/\partial y_i & \partial v/\partial y_i \end{bmatrix}$$
$$\doteq \begin{bmatrix} x_{i-1}-x_i & y_{i-1}-y_i \\ x_{i-2}-x_i & y_{i-2}-y_i \end{bmatrix}^{-1} \begin{bmatrix} u_{i-1}-u_i & v_{i-1}-v_i \\ u_{i-2}-u_i & v_{i-2}-v_i \end{bmatrix} \quad (17)$$

or
$$\begin{bmatrix} f''(x) \\ f'(x) \end{bmatrix}$$
$$\doteq \begin{bmatrix} 2! & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} (x_{i-1}-x)^2 & (x_{i-1}-x) \\ (x_{i-2}-x)^2 & (x_{i-2}-x) \end{bmatrix}^{-1} \begin{bmatrix} f_{i-1}-f(x) \\ f_{i-2}-f(x) \end{bmatrix} \quad (18)$$

SYSTEMS OF EQUATIONS

Clusters may be used to solve any system of equations, as

$$\left.\begin{aligned} f(x, y) &= 0 \\ g(x, y) &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (19)$$

Thus, if (x_{i-2}, y_{i-2}), (x_{i-1}, y_{i-1}), (x_i, y_i) are three sufficiently close approximations to a solution of (19), then

$$x_{i+1} \doteq \frac{\phi\,(f, g, x)_i}{\phi\,(f, g, 1)_i}\,, \qquad y_{i+1} \doteq \frac{\phi\,(f, g, y)_i}{\phi\,(f, g, 1)_i}\,, \quad . \quad (20)$$

is a better one.

In the special case of one equation

$$f(x) = 0\,, \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

the method of solution becomes the secant method,

$$x_{i+1} \doteq \frac{x_{i-1} f(x_i) - x_i f(x_{i-1})}{f(x_i) - f(x_{i-1})}\,. \quad . \quad . \quad (22)$$

If it is suspected that (21) has a pair of double, nearly double, or complex roots, the geometric determinant may be used to obtain

$$x_i^2{}_{+1}\,\phi\,(f, x, 1)_i + x_{i+1}\,\phi\,(x^2, f, 1)_i + \phi\,(x^2, x, f)_i \doteq 0\,. \quad (23)$$

Either root of the quadratic in the complex plane is then followed.

Sets of relations such as (20), (22) or (23) may be compactly expressed in terms of plats, as

$$[x_{i+1}\ y_{i+1}] \doteq [0\ 0\ 1] \begin{bmatrix} f_i & g_i & 1 \\ f_{i-1} & g_{i-1} & 1 \\ f_{i-2} & g_{i-2} & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_i & y_i \\ x_{i-1} & y_{i-1} \\ x_{i-2} & y_{i-2} \end{bmatrix}\,. \quad (24)$$

INTEGRATION

Integration methods may be expressed in different forms, according to the approach taken. Thus, by considering $\phi\,(x, f) \doteq 2f dx$, one may derive

$$\int_{x_0}^{x_n} f(x)\,dx \doteq \frac{1}{2}\left[\begin{vmatrix} x_n & f_0 \\ x_0 & f_n \end{vmatrix} + \sum_{i=1}^{n} \begin{vmatrix} x_i & f_i \\ x_{i-1} & f_{i-1} \end{vmatrix}\right]. \quad (25)$$

The relation $\phi\,(x, y, 1) \doteq dx dy$ gives

$$\int_S \int f(x, y)\,dx dy \doteq (1/3!) \sum_S \sum (f_{i,j} + f_{i-1,j-1} + f_{i-2,j-2})\,\phi\,(x, y, 1)_{i,j}\,. \quad . \quad (26)$$

where the z-axis is vectorially positive to the path $(x_{i-2}, y_{i-2}), (x_{i-1}, y_{i-1}), (x_i, y_i)$.

Or, integration of higher order cluster expansions of the function gives

$$\int_{x_0}^{x_{2n}} f(x)\,dx \doteq \sum_{i=2}^{2n} [(2 - 1/r_i)\,f_i + (1/r_i + 2 + r_i) f_{i-1} + (2 - r_i)\,f_{i-2}]\,\Delta_i x/6\,. \quad . \quad (27)$$

where $\Delta_i x = x_i - x_{i-2}$, $\quad r_i = (x_i - x_{i-1})/(x_{i-1} - x_{i-2})$.

CRITICAL VALUES OF A FUNCTION

Just as the zeros of a function $f(x)$ may be located by the iterative scheme

$$x_{i+1} \doteq \frac{\phi\,(f, x)_i}{\phi\,(f, 1)_i}\,, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

so the poles and stationary values of the function and the stationary values of its derivative are located as

$$x_{i+1} \doteq \frac{\phi\,(xf, 1)_i}{\phi\,(f, 1)_i}\,, \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

$$x_{i+1} = \frac{\phi\,(f, x^2, 1)_i}{2\phi\,(f, x, 1)_i}\,, \quad . \quad . \quad . \quad . \quad . \quad (29)$$

and
$$x_{i+1} \doteq \frac{\phi\,(f, x^3, x, 1)_i}{3\phi\,(f, x^2, x, 1)_i}\,, \text{ respectively.} \quad . \quad (30)$$

LEAST SQUARE CURVE FITTING

A function of the form $F(a, b, x, y, z) = 0$ may be best fitted to a set of n points (x_k, y_k, z_k) by minimising the sum of the squares of the residuals

$$f(a_i, b_j) = \sum_{k=1}^{n} F^2\,(a_i, b_j, x_k, y_k, z_k)\,.$$

The coefficients are determined by

$$a_{i+1} \doteq \frac{\phi\,(f, a^2, 1)_{i,j}}{2\phi\,(f, a, 1)_{i,j}}\,, \qquad b_{j+1} \doteq \frac{\phi\,(f, b^2, 1)_{i+1,j}}{2\phi\,(f, b, 1)_{i+1,j}} \quad (29)$$

DIFFERENTIAL SYSTEMS

The first three points of the curve

$$f(x_0), f(x_1), f(x_2), \ldots, f(x_{i-2}), f(x_{i-1}), f(x_i)$$

of the differential equation

$$F(f'', f', f, x)=0, \qquad f(x_0)=a, \qquad f'(x_0)=b$$

are obtained from the Taylor expansion

$$f(x)-f(x_0) \doteq [(x-x_0)^2 \; (x-x_0)] \begin{bmatrix} 1/(2!) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} f''(x_0) \\ f'(x_0) \end{bmatrix}, \quad (31)$$

where the error in $f(x)$ will not numerically exceed

$$\frac{(x-x_0)^2 \; (f''(x)-f''(x_0))}{3!} .$$

Proceeding to the next point, estimates of the values of the function, $f_0(x_{i+1})$, and of its derivatives there, $f_0'(x_{i+1})$ and $f_0''(x_{i+1})$, are obtained from (12) and (18).

These values are corrected by putting

$$f_1''(x_{i+1})=f_0''(x_{i+1})+\text{a small number},$$

and repeating the cycle (32), (33),

$$\begin{bmatrix} f_j'(x_{i+1}) \\ f_j(x_{i+1}) \end{bmatrix} \doteq \begin{bmatrix} x_{i+1}-x_i & 0 \\ -(x_{i+1}-x_i)^2/2! & x_{i+1}-x_i \end{bmatrix} \begin{bmatrix} f_j''(x_{i+1}) \\ f_j'(x_{i+1}) \end{bmatrix} + \begin{bmatrix} f_i' \\ f_i \end{bmatrix} \quad (32)$$

$$f_j''_{+1}(x_{i+1}) \doteq [0 \;\; 1] \begin{bmatrix} F_j & (x_{i+1}) \; 1 \\ F_{j-1} & (x_{i+1}) \; 1 \end{bmatrix}^{-1} \begin{bmatrix} f_j'' & (x_{i+1}) \\ f_j''_{-1} & (x_{i+1}) \end{bmatrix} . \quad (33)$$

until $f_j(x_{i+1})$ converges, to $f(x_{i+1})$. The error in $f(x_{i+1})$ will then not numerically exceed

$$(1/3)(x_{i+1}-x_i)(x_i-x_{i-1})(f_i''_{+1}-f_i''_{-1}) .$$

Terminal boundary values, as $f(x_0)=a$, $f'(x_n)=b$, may be handled by adjusting the value of $f'(x_0)$ by (22) until $f'(x_n)-b=0$. This will require about six complete scans of the curve.

With a system of differential equations, the vectors become matrices.

AN ILLUSTRATIVE EXAMPLE

An example has been included here simply to show that this is a "vest pocket" tool, instantly available to the scientist and engineer.

Suppose the solution is required of the system of equations

$$\begin{aligned} f(x, y) &= x+3 \log x-y^2=0 \\ g(x, y) &= 2x^2-xy-5x+1=0 \end{aligned} \quad . \quad . \quad (34)$$

nearest to the point $x=3, y=2$, which is an estimate obtained graphically. This example is taken from pages 203-206 of Ref. 2.

With no reason to suspect a multiple solution, it is decided to use a linear technique and, therefore, the linear cluster of the system, $\phi(f, g, 1)_i$, as the common denominator. By symbolic cancellation, the numerators are now obvious. The cluster formulae are then

$$x_{i+1} \doteq \frac{\phi(f, g, x)_i}{\phi(f, g, 1)_i} , \qquad y_{i+1} \doteq \frac{\phi(f, g, y)_i}{\phi(f, g, 1)_i} \quad . \quad (20)$$

Note that the computation will involve the evaluation of third-order determinants, a process that is not too difficult on desk calculators with quotient dial locks. However, the matricial form will be easier for those not expert with such calculators, so the conversion is made to a plat form that will yield terms (20), using principle (10). The formula is now

$$[x_{i+1} \; y_{i+1}] \doteq [0 \;\; 0 \;\; 1] \begin{bmatrix} f_i & g_i & 1 \\ f_{i-1} & g_{i-1} & 1 \\ f_{i-2} & g_{i-2} & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_i & y_i \\ x_{i-1} & y_{i-1} \\ x_{i-2} & y_{i-2} \end{bmatrix} . \quad (24)$$

The process is started with the estimate, $(x_0, y_0)=(3, 2)$, and two nearby points, as $(x_{-1}, y_{-1})=(3, 2.2)$, $(x_{-2}, y_{-2})=(3.3, 2)$. The corresponding values of the functions are obtained from (34).

The operation $A^{-1}B$ is performed by the simple process of reducing the first three columns of the augmented matrix to the identity matrix, eliminating by addition or subtraction. The first results are $(x_1, y_1)=(3{\cdot}5028519, 2{\cdot}2719903)$, giving $(f_1, g_1)=(-0{\cdot}025822297, 0{\cdot}06723738)$.

The course of the iteration is given in Table I.

TABLE I.

i	x_i	y_i	f_i	g_i
−2	3·3	2	0·85554174	−0·32
−1	3	2·2	−0·40863618	−2·6
0	3	2	0·43136373	−2
1	3·5028519	2·2719903	−0·02582297	0·06723738
2	3·4848531	2·2600028	0·00379395	−0·01164103
3	3·4875657	2·2616956	−0·00013417	0·00058818
4	3·4874416	2·2616278	0·00000191	−0·00000525
5	3·4874428	2·2616286	0·00000015	0·00000015
6	3·4874428	2·2616286		

The reader will find that subtractive error is likely to become excessive in higher order approximation methods, as (23) or (29), unless this effect is minimised by translating the formula to its i^{th} result, as

$$(x_{i+1}-x_i)^2 \begin{vmatrix} f_{i-1}-f_i & x_{i-1}-x_i \\ f_{i-2}-f_i & x_{i-2}-x_i \end{vmatrix} +$$

$$+(x_{i+1}-x_i)\begin{vmatrix} (x_{i-1}-x_i)^2 & f_{i-1}-f_i \\ (x_{i-2}-x_i)^2 & f_{i-2}-f_i \end{vmatrix} + f_i \begin{vmatrix} (x_{i-1}-x_i)^2 & x_{i-1}-x_i \\ (x_{i-2}-x_i)^2 & x_{i-2}-x_i \end{vmatrix} \doteq 0. \quad . \quad . \quad . \quad (23)$$

ACKNOWLEDGMENTS

The theory of the geometric determinant was explored by Vandermonde. The Lagrangian method of interpolation is generalised in (4). (25) and (27) are generalised forms of the trapezoidal and Simpson's rules, respectively, for integration.

Among modern writers, the notion of a determinantal notation was probably first due to Whittaker and Watson[3], although a different notation is used here, emphasising the intimate relationship between clusters and plats, again our terms. Milne[1] first derived the one-dimensional form of (13), which has since been generalised to (17).

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Graduates' and Students' Section

Lecture

The last lecture of 1958 was given on 9th December by Mr. E. C. Bowyer, the Director of the S.B.A.C. His subject was the somewhat cloudy "Future of the British Aircraft Industry."

In a brief review of the past Mr. Bowyer pointed out that crises were not a new phenomenon in the Industry. At present it was still expanding, especially in the guided weapon field. This year it would export £150m of aircraft and parts, or 11 per cent of engineering exports. Aircraft were particularly valuable exports as they required a minimum of raw material and sold for £15 per lb. of weight as compared with 5/- per lb. of weight for motor cars. The Industry had served the country well, having contributed to the development of electronics, fuels, light alloys, hydraulics, and so on, and since the Second World War had accounted for over £800m of exports.

The present high volume of exports, the lecturer averred, was due to past research and development and this in fact was the lifeblood of the Industry. The recent White Papers on defence had caused alarm as it was thought that the scale of research and development would diminish. Mr. Bowyer felt that Government aid must continue for both military and civil aircraft development. This could take many forms: the direct financing of research, the issuing of specifications for new military aircraft with an eye on the N.A.T.O. market, and the ordering of civil transport aircraft for Transport Command to facilitate faster flight proving—witness the U.S.A.F. ordering of the Boeing KC.135 of which the Boeing 707 is a derivative.

In the long term view Mr. Bowyer foresaw the market continuing to expand, especially in the air-freighter field, and fares falling as more efficient aircraft were utilised. The short term view included a "dip" in the export curve.

Mr. Bowyer concluded his interesting lecture by remarking that every major breakthrough in science had come from men and women in the same age bracket as that of the Graduates and Students of the Society: the future therefore lay in their hands. W.G.W.

Courtesy of "The Autocar"

Building the Cooper Car.

The Spring Lecture Programme

Accompanying this issue of the JOURNAL is the lecture card for the Spring Session of 1959. Four lectures are scheduled in addition to the Annual General Meeting and film show, which is fixed for Wednesday 4th March.

The first lecture is to be given on 14th January by Mr. D. J. Lambert, of Vickers-Armstrongs (Aircraft) Ltd. Mr. Lambert has played a very big part in the overwhelming success of the Viscount, and his lecture will be extremely interesting.

Further lectures are to be given by Lt.-Cdr. D. J. Whitehead, the well-known test pilot from Blackburns, Mr. J. Martin, Director of the Martin-Baker Aircraft Company, and a member of the staff of the U.S. Air Attaché. More news will be given of these lectures in future issues.

All lectures will again be preceded by free coffee from 7 p.m.

Cooper Visit

To visit a firm like the Cooper Car Co. of Surbiton is a most refreshing experience for those in the Aircraft Industry. We have become too much accustomed to the complex organisation which seems necessary to produce anything.

Those familiar with the racing successes of Coopers this year (two championship Grand Prix wins, and the Formula 2 championship) and the really excellent finish and attention to detail which they build into their cars might be excused for expecting a large factory full of busy technicians. Instead we saw how the original garage premises had been extended and adapted for the regular production of racing cars.

Mr. Owen Maddock, who is not just one of the design office (he *is* the design office), first showed us the welding jigs for the tubular steel chassis frames for the three models in current production. This is the heart of the car, since all the components are bolted or screwed in position, there being no subsequent riveting or welding of the frame.

Coopers use large tubes and allow them to take bending loads, so their chassis is not a space frame in the true sense of the word. We were told that experience has shown this to be both simple to make and rugged, and certainly their record of reliability in races this year supports this.

Very little of the work is subcontracted, and items as large as wheels were being turned from magnesium castings. An exception to this is the aluminium bodies which are fully detachable, including the undertray, and provide accessibility comparable only to the Dart engine installation on the Viscount. The body formers which act as the jig for the panel beaters to work to are made from light steel strip, which they find both cheap and easy to alter if required.

We were shown the finished prototype of the new sports car, and Mr. Maddock was kept busy answering endless questions. As we left we were still scratching our heads at their ability to turn out a car which more than holds its own as an engineering job alongside products from the vast firms in the motor industry. P.T.R.

THE LIBRARY

Reviews

GUIDED MISSILES — OPERATIONS, DESIGN AND THEORY. *U.S. Department of the Air Force. McGraw-Hill. London, 1958. 575 pp. Illustrated. 62s.*

This 575 page book is based on a Military Training Manual first written three years ago at the U.S. Air Force Missile School in Colorado. It is obviously intended for the instruction of military personnel, but an effort is made to stress the fundamentals of missile design, and most aspects of the subject are dealt with, albeit at times in a rather elementary fashion. After the usual historical introduction, Chapters 2 and 3 discuss missile aerodynamics and propulsion in simple terms, with numerous diagrams and illustrative graphs. The treatment of these subjects shows a distinct tendency to be unsound on basic principles; for example the definitions associated with the laws of motion would undoubtedly have disturbed Newton, since they appear to confuse force, momentum and weight. Sections follow on the physical principles involved in missile design, including useful explanations of wave modulation methods and the application of basic optical laws to the manipulation of electromagnetic radiation for communications and guidance purposes. A short section on the physics of transistors is interesting but seems slightly out of keeping with the rest of the text.

Chapters 5 and 6 on control and guidance components and basic techniques are the most useful in the book. They give a very understandable account of the basic design features of all the main components of typical missile systems and the associated electronic circuitry. Transducers, pick-offs, computing devices and data-transmitting systems are described, but there is a noticeable gap as regards servomechanisms and closed-loop servo systems. Chapters 7-9 on control and guidance systems are disappointing and give the impression of having been written by a contributor familiar only with very early examples of missile design.

Throughout the book the text is profusely illustrated by exceptionally clear diagrams, both line and half-tone, many of them full-page. The standard of illustrations is indeed higher than average, but is not everywhere matched by that of the text, which is sometimes diffuse, occasionally inaccurate and often a trifle naïve; especially when the military potentialities of missiles are discussed. In general the subject matter of the book should be easily grasped by a reader with mathematics and science to about Inter B.Sc. standard. It is readable, well set out and, for new entrants to guided missile work, forms a good introduction to all aspects of the subject. More advanced readers will be surprised to learn (p. 28) that the energy of a moving body transformed into a temperature is known as the heat barrier; no doubt any shock to the nervous system will be eased by the fact, given in the section on propulsion, that ethyl alcohol is not toxic unless taken to excess.—W. H. STEPHENS.

MECHANICS OF MACHINES. *J. Hannah and R. C. Stephens. Edward Arnold, London, 1958. 237 pp. Illustrated. 18s.*

This book is intended to cover the theory of machines syllabus for students taking the first year of an engineering degree or diploma course. It is claimed that a "concise but thorough statement of the theory" is given in this book. Unfortunately this is not always so.

There is evidence of lack of precision in various chapters. In particular, in the discussion of simple harmonic motion, there are several statements in the form of $\theta/\alpha=C$, where C is constant. This, of course, is not simple harmonic motion, also it is a pity to use α for angular acceleration where $\ddot{\theta}$ is meant. Further, in the typical solutions to problems, the mass acceleration forces are not put in their proper places, causing confusion in the mind of the student. The proper statement of d'Alemberts' principle has not been included.

Nevertheless, the great number of examples given will be of considerable help to the student.—K. L. JACKSON.

BRITISH WEATHER IN MAPS. *J. A. Taylor and R. A. Yates. Macmillan, London, 1958. 256 pp. Illustrated. 21s.*

Two geographers from University College, Aberystwyth have embodied part of their first year course in practical climatology in a book which attempts to teach students how to recognise air masses covering the British Isles.

Instead of describing how a practising meteorologist analyses and "draws up" his maps to show the weather situation noting as he does so the distributions of cloud, visibility, and so on, the student is enjoined to draw separate maps of eight different weather elements. This makes appreciation of the scene more difficult, especially as the maps shown are on the back of the page showing the observations. Many of the isopleths, of which the authors almost make a fetish, are nonsense anyway, as, for instance, where isopleths of visibility are drawn across the sea or central Scotland where there are no observations used. Not only have they failed to use any but coastal stations in Scotland, but they say, without reasoning it out, that they have used the 06 G.M.T. observations to eliminate the effect of diurnal variations: this is ridiculous.

Early in the book an account of the physical basis of the subject is attempted. There are many subtle points about lapse rates which can be avoided if care is used, but they stumble at almost every one. Do they know, for instance, that the lapse rate of an ascending parcel of air is different in stable and unstable surroundings? Why do they say on one page that the dry adiabatic lapse rate can be measured and is constant, and on the next that it is slightly curved when drawn on linear graph paper? It is so simple to derive it from first principles and settle the matter. Their diagrams imply that the temperature excess of an ascending parcel of buoyant air increases as it rises, when quite the opposite is known to be the case! Fig. 18, with its squiffy inversion, is silly; and Fig. 45, which is borrowed, shows the motion of the warm air in a depression incorrectly. They give no discussion of upper winds; and a statement of how the wind varies with height would make nonsense of their concept of air masses being modified only by vertical motion and surface influences.

The descriptions of humidity, adiabatic, pressure gradient and units of atmosphere pressure, are bungled; a facile paragraph on "trigger actions" ignores castellanus cloud formation. The meaningful word "discontinuity" is murdered by being defined as a region of large gradient. What will the good student think when he finds out such things? He will wish he had learned the calculus, or Spanish, or chemistry, instead.

There are many geography books which are most absorbing to the adult mind trained in an academic subject; but, after the elementary stages at which the youngster is introduced to the world, geography—like meteorology—

should be abandoned as an A-level and undergraduate subject, and, on account of its complexity, should be studied by postgraduates only. This book is full of careless errors which could easily be corrected by reference to the books listed for further reading; it demonstrates that geography, as taught at these intermediate levels, is not a sound academic discipline. The enthusiasm of the authors is in stark contrast with their baneful indifference to scientific detail, and the notable competence of the publishers with the pointlessness of the tedious exercises recommended to the reader.—R. S. SCORER.

BEHIND THE SPUTNIKS—A SURVEY OF SOVIET SPACE SCIENCE. *F. J. Krieger. Public Affairs Press. U.S.A., 1958. 380 pp. Illustrated. 6 dollars.*

One of these days, perhaps a century or three hence, many "books" will be written about the history of astronautics. ("Books," in quotes, for who is to say what form they will take in eras as far removed from ours as we are from Faraday or Newton?) Of course, many have been written already, but these later ones will be more important.

In their (we hope) more enlightened times, the full significance of technological progress in the whole story of mankind will be recognised, but there is yet another, and greater, reason why the subject will be taken more seriously than is, for example, the history of aeronautics by anyone today. Aeronautics provides a better form of terrestrial transport, or method of waging war, but astronautics promises a tremendous forward step in human evolution. At the very least, within only a few generations, it will be seen as equivalent to the great developments in oceanic voyaging of the Renaissance period, but eventually it may prove even more important than these.

Our future historian will find little difficulty in discovering the origins of space travel in those basic impulses of curiosity, wonder and ambition which are inherent in our species because of their high evolutionary survival-value; in early romantic writings, in preliminary theoretical studies, and in the first crude experiments of dedicated amateurs. The next step will be obvious, too; as with so many other things, their military usefulness ensured the development of the first devices of astronautical significance—the various German rockets of the Second World War.

However, he might hesitate in drawing his conclusions about the next phase. Did the two major powers of the late 20th century embark independently on the conquest of space, or did one of them, at least, do this only because of a cynical desire to win a competition for political prestige—the one, moreover, which did in fact win the first round of such a competition, and which may yet win them all?

An American who was closely concerned with the early stages of their satellite programme once observed to me that, but for the prior publication of a number of convincing papers by the British Interplanetary Society, he doubted whether the project could have been "sold" to the U.S. authorities, and that if it had not been (in a great blaze of publicity), he believed the Russians would have taken no interest at all in space-flight. This is an interesting point of view, in which I think there may be some grains of truth, though I am sure it is far from representing the whole truth.

Krieger's interesting book is very relevant to this question. It presents the results of a study made, with just that characteristic solemn touch of Teutonic thoroughness, by the Rand Corporation for the U.S.A.F. Being based, to quote the author's preface, "entirely on the open literature," it hardly lives up to its sub-title: "A Survey of Soviet Space Science," but makes fascinating reading nonetheless. Official statements, entries in encyclopedias, and articles from newspapers, magazines and books, are reproduced (in English, of course). Most of the latter are of the good "popular science" variety, and make very frequent reference to similar American and British works. One very interesting article (by Academician Ginsburg) deals with the use of artificial satellites to verify experimentally the general theory of relativity.

The volume begins with a quotation from Tsiolkovsky: "The Earth is the cradle of the mind, but one cannot live forever in a cradle", and many of the articles also open with a tribute to this first-of-all of the scientific pioneers of astronautics. His earliest writings on the subject appeared in the closing years of the 19th century, so that in this field at least, Russian claims to priority cannot be written off as mere manifestations of a national inferiority complex. It is interesting, too, to read of experiments by the Russians Tsander and Tikhonravov, with liquid-propellant rockets, in 1932—only a few years after Goddard and the V.f.R. A Russian aircraft with a liquid propellant rocket engine apparently was flying in 1942, the airframe being attributed to Bolkhovitinov and the engine to Dushkin. Reference is made to later examples capable of over 1,200 m.p.h., with engines weighing about 300 lb. for 6,500 lb. thrust.

In the pre-war years, Russia (like America, Germany and Britain) had her rocket and interplanetary societies, and the same flood of literature on the subject, mostly of a semi-technical and propagandist nature. From 1953 onwards, there is a noticeable increase in the number of favourable references to space flight by established Soviet scientists and engineers. Soon after this, the Academy of Sciences of the U.S.S.R. formed its "Interplanetary Communications (*i.e.* Astronautical) Commission." This is chaired by Professor Sedov who now attends the various international congresses on space-flight, and who is a noted gas-dynamicist. Among its 27 members are the famous physicist, Kapitza, and the Bolkhovitinov and Ginsburg mentioned earlier in this review. The Academy, of course, is a very powerful body approximating to a combination of the Royal Society, the D.S.I.R. and part of the M.o.S.

The picture which emerges from all this is overwhelmingly one of a quite remarkable similarity to that in the west—of a long-standing and spontaneous Russian interest in astronautics, which has always been encouraged by the authorities (for example, they treated Tsiolkovsky extremely well), and is now enjoying even more intensive patronage of this kind. No doubt this is largely due to a desire to keep up with, or surpass, the American Joneses, but there is no reason to believe it is entirely for that reason.

Such a view is additionally supported by a couple of Russian popular science films recently shown in this country, the second of which (Sovexportfilm "Blazing a Trail to the Stars") was a really impressive effort, clearly indicating the likely course of events in astronautics for the next thirty years or so. If anyone over here would prefer a more staid guidebook to the subject and period, they should read the thick White Paper (Union Calendar No. 695, House Report No. 1758) which is the report of the U.S. Congressional Select Committee on Astronautics and Space Exploration. Together with the recent transformation of the N.A.C.A. into N.A.S.A., it clearly indicates the intention of the Joneses to keep up with the Kruschevs.

No doubt they, too, were influenced by Dr. Teller's alleged reply to the Committee's question about what he expected to find on the Moon: "The Russians," he said.—A. V. CLEAVER.

WERKSTOFF-HANDBUCH DER DEUTSCHEN LUFTFAHRT. *Teil I. Metallische Werkstoff. Edited by the Standards Office (Aeronautics) at the request of the Federal Defence Minister. Beuth Vertrieb G.m.b.H., Cologne, 1958. DM.191.50. (In German.)*

This collection of specifications, in ring-book form, with introductory explanations and definitions, applies also to civil aviation; until September 1957 it was edited by the Federal Association of the German Aircraft Industry. The new standards are to supersede the former *Fliegwerkstoffe* (an unhappy expression of the Hitler period, associating aircraft materials vaguely with fly-paper); they also embody or cover British, French and U.S.A. specifications, as an aid for production under licence in Germany.

Each material is covered by a specification sheet. This consists of a table stating name and code number of the material, the state for which its properties are specified (usually, " as supplied "), the surface condition (*e.g.* rolled and descaled), the shape in which the material is supplied (with specified tolerances), the minimum strength properties according to standard tests, the chemical constitution, heat-treatment by the user, special properties of the material (*e.g.* suitability for welding), recommended applications and application limits (*e.g.* maximum admissible service temperature); specific weights, heat conductivity, coefficient of expansion, magnetic properties and so on, and equivalent material specifications in the three countries named. The code number gives the general class of the material and its state of treatment; "1.4544.9", for instance, signifies a steel ("1") of specified austenitic Cr-Ni alloy (" 4544 "), specially pre-treated before supply (" 9 "); "2.0804.2", similarly, denotes a drawn tin bronze in the semi-hard state. This key number must be on the material when supplied, on completed components, on drawings, parts lists, and so on.

In the comparison with non-German specifications, four cases of equivalency or interchangeability are used in the tables: identical specifications; unrestricted substitute materials; conditionally substitute materials, and materials which, though different, may replace those to foreign specifications after expert investigation in each case of application. The U.S.A. excel in having not less than six systems of standardisation of metallic materials (AMS, FED, MIL, AN, SAE, AISI), France three (AIR, AFNOR, BNA), while Britain has merely two systems (BS, DTD). However, only a minor part of the British material specifications has been embodied—for reasons left to our imagination.

The present collection covers 38 steels, including 14 low-alloyed carbon steels, 20 copper and silver alloys, and 27 light alloys. This covers everything aeronautical, including power plants, instrumentation, and equipment, even tool steels.

All specifications are in tables, without any text. This practical, clear and comprehensive representation can be recommended to authors of specifications in this country (who still consider them as literary efforts). Less recommended is the binding of the volume which is demonstratively unable to resist the muscular efforts of H.M. Post Office.—A. R. WEYL.

ZEITSCHRIFT FUR ANGEWANDTE MATHEMATIK UND PHYSIK (ZAMP), Journal of Applied Mathematics and Physics. *Festschrift Jakob Ackeret. Birkhauser Verlag, Basel, 1958. 777 pp. Illustrated. Swiss francs 24.*

This special issue of the Journal of Applied Mathematics and Physics is dedicated entirely to Jakob Ackeret, Professor at the Eidgenoessische Technische Hochschule, Zurich, on the occasion of his 60th birthday. The first part of the volume gives a picture of what Ackeret is and what he has become—to use the motto of the introductory discourse " Werde was du bist "—in the form of a biography and a bibliography of over a hundred articles, papers and text books. Also included are contributions from official bodies and from industry of his own country, with emphasis on his influence, as a scientist, on engineering in general and on defence. Other contributions in this part refer to Ackeret's earlier activities at Goettingen, where he was a pupil of Prandtl, and to the driving force he put behind the development of ballistics and rockets in Switzerland. All these contributions are in German.

The second and by far the greater part of this special volume consists of contributions of original papers, in English, German and French. After a witty address by Professor von Kármán, who, interestingly enough, points out the apparent influence of " great masters " on the development of prominent personalities, 58 papers follow all written for the occasion and many of them relate to Ackeret as the originator of the basic idea or as a prominent contributor to its development.

These papers cover a wide field of physics and mathematics as applied to aerodynamics and allied branches. The distribution of the languages in which these papers are written in this issue is about the same as in the periodical throughout recent years, about half in English and half in German, with an occasional paper in French. In the present volume the contributions come from many parts of the Western World: from Germany (22), U.S.A. (17), Switzerland (7), Holland (2), France (4), Canada (2), Italy (1) and from Great Britain (2).

The variety of problems, on boundary layers, cascades, supersonic flow and so on presented by different authors of international reputation lends exceptional value to this book, particularly as most of the subjects treated are closely related to current problems in aeronautical engineering and are, as is customary with ZAMP, far from being primarily of academic interest. Thus, this special issue makes attractive reading, provided that the reader is sufficiently familiar with German or French. Although summaries in English are added these do not give an adequate account of the contents of the paper. Publishers of periodicals (or even of textbooks) which are likely to attract attention over the greater part of the world would increase their circulation and serve an even more useful purpose if the summary in a language other than that of the original text were not treated as a mere formality but were given in greater detail than the summary in the language of the original paper.

Retaining a usual feature of this Swiss periodical, the print and the paper in this special issue are as clear and white as the skies and the glaciers of this fortunate country.—E. S. KRAUSS.

Additions to the Library

Aircraft Fatigue Handbook, Volume II. Aircraft Industries Association (U.S.) 1957. *Not available for loan.*

Aircraft of the Royal Air Force 1918-58. Owen Thetford. Putnam, London. 1958. 533 pp. Illustrated. 50s. The previous edition of this book was reviewed in the JOURNAL of August 1957 and except in one particular, there would appear to be no reason to differ materially from the opinion of A.S.C.L. The addition of mark numbers to the aircraft drawings makes the book even more valuable as a reference work.

Application of Atomic Engines in Aviation. G. N. Nesterenko *et al.* U.S. Office of Technical Services, Washington. 1957. 184 pp. Illustrated. 27s. A translation prepared at Wright-Patterson Air Force Base from the Russian text of three members of the Military Press of the Ministry of Defence of the U.S.S.R. There is a 33-item bibliography.

Army Missiles, Rockets. U.S. Department of the Army, U.S.G.P.O., Washington. 1958. 40 pp. Illustrated. 2s. 8d. A short description, with no technicality, of nine surface-to-surface and five surface-to-air missiles. A list of U.S. Army "firsts" (from 1953) is appended.

Bibliography of Space Medicine. U.S. Department of Health. U.S.G.P.O. 1958. 49 pp. 3s. 2d. 381 references divided into ten subjects with an author index.

Development of the Aeroplane. P. W. Brooks (Cantor Lecture). Royal Society of Arts (*Author's Typescript*). 1958.

DHC-4 Caribou, The. De Havilland Aircraft of Canada Ltd. 22 pp. Photographs.

Discussion on Observations of the Russian Artificial Earth Satellites and their Analysis. Proceedings A. Royal Society No. 1252, Volume 248. 143 pp. 18s. The sixteen papers presented to the Royal Society at the November 1957 meeting, under the leadership of Professor H. S. W. Massey. No Russian contribution.

Fundamentals of Gas Dynamics. Howard W. Emmons. Oxford University Press, London. 1958. 749 pp. Illustrated. 140s. *To be reviewed.*

Gross Pattern of Injury of 109 Survivors of Five Transport Accidents. A. Howard Hasbrook. Aviation Crash Injury Research of Cornell University. Phoenix, Arizona. 1958. 54 pp. Reviews such material as site, frequency and seriousness. Seating circumstances are particularly investigated.

Handbook of Automation Computation and Control, Volume I Control Fundamentals. E. M. Grabbe *et al.* John Wiley, New York, Chapman and Hall, London. 1958. 1017 pp. Illustrated. 136s. *To be reviewed.*

Handbook on Torsional Vibration, A. E. J. Nestorides (Compiler). British Internal Combustion Engine Research Association. C.U.P., London. 1958. 664 pp. Illustrated. 110s. *To be reviewed.*

Hearings Before Sub-committees of the Joint Committee on Atomic Energy. U.S. Congress. U.S.G.P.O., Washington. 1958. 232 pp. 5s. 5d. "To provide information for the Congress and the public on what measures are being taken and are contemplated in the field of space propulsion and exploration."

Hearings Before the Select Committee on Astronautics and Space Exploration. U.S. Congress. U.S.G.P.O., Washington. 1958. 1542 pp. Illustrated. 40s. 6d. "To conduct a thorough and complete study and investigation with respect to all aspects and problems relating to the exploration of outer space and the control, development, and use of astronautical resources, personnel, equipment and facilities."

Jahrbuch 1957 der Wissenschaftlichen Gesellschaft fur Luftfahrt. H. Blenk (*Editor*). Vieweg, Berlin. 1958. 512 pp. Illustrated. DM 58. This annual contains some 50 papers, by most of the leading German authorities, including the papers of the W.G.L.-D.V.L. 1957 Conference. There are also papers in English by J. C. Houbolt, of N.A.C.A., A. H. Hasbrook of Aviation Crash Injury Research and W. A. Good of Silver Spring, Maryland. Full-length obituaries of Euler and Heinkel are included.

Jet Age Planning. A report of progress and developments as of July 1957. U.S. Civil Aeronautics Administration. U.S.G.P.O. 1957. 23 pp. 2s. 3d. Considers noise, airports, traffic control and navigation aids.

Leader Behavior and Leadership Ideology of Educational Administrators and Aircraft Commanders. A. W. Halpin. 1955. Reprint from *Harvard Educational Review.*

Missiles, Rockets and Satellites (a bibliography in 5 parts). U.S. Dept of the Army. U.S.G.P.O. 1958. 10s. 5d. I—U.S.S.R.; II—United States; III—Great Britain, France, etc.; IV—Technology, Means and Methods and V—Earth Satellites and Space Eploration.

Prediction of Ballistic Missile Trajectories from Radar Observations, The. I. I. Shapiro. McGraw-Hill, London. 1958. 208 pp. Illustrated. 54s. 6d. *To be reviewed.*

Principles of Electronics. H. Buckingham and E. M. Price. (*Second Edition.*) Cleaver-Hume, London. 1958. 419 pp. Illustrated. 17s. 6d. The second edition of a book first published in 1953 in the "Cleaver-Hume Electrical Series." It is intended to give a good grounding in electronics to those following a general electrical engineering course. This new edition contains two new chapters—on transistors and on magnetic amplifiers—and questions to test the progress of the student, in addition to many minor revisions.

Proceedings of the National Specialists Meeting on Dynamics and Aeroelasticity. Institute of the Aeronautical Sciences in cooperation with Texas Section, I.A.S., New York. 1958. 135 pp. 6 dollars (non-members), 3.50 dollars (members). Thirteen papers representing the unclassified portions of the meeting. Subjects covered include aeroelasticity, aerodynamic loads, structure loads, stability and control.

Proceedings of VIIIth International Astronautical Congress, Barcelona 1957. F. Hecht (*Editor*). Springer-Verlag, Wien. 1958. 607 pp. Diagrams. £8 10s. A collection of 46 papers read at the Congress, which was held immediately after the launching of the first Russian satellites on 4th October. 35 of the papers are in English, including "The Problem of Variable Thrust" by W. N. Neat, "Space Law" by A. G. Haley and a paper on the observations from a balloon capsule at 30 kilometres by D. G. Simons. There are 3 papers in French and 4 in German; 4 of the 5 Russian papers (English abstracts) deal with Earth satellites.

Sound of the Helicopter, The. Bell Helicopter Corp., Fort Worth, Texas. 3 pages, charts. A pamphlet including three charts showing Overall Noise against Distance, a Comparison of Noise Levels of various Vehicles in Motion, and Overall Noise Levels.

Status and Economic Significance of the Airline Equipment Investment Program. P. W. Cherington. 43 pages. Unpublished. A report prepared by the Professor of Business Administration at Harvard for President Eisenhower's Special Assistant for Aviation. It comments on the U.S. Airlines programme to expend 2.8 billion dollars over the next five years and analyses the present and prospective situation.

Technische Hydro-und Aeromechanik. W. Kaufmann (*Second Edition.*) Springer-Verlag, Berlin. 1958. 382 pp. Diagrams. DM 37.50. The first edition, published in 1954, was reviewed in the JOURNAL of March 1955 (p. 229) with the conclusion "On the whole the book provides engineers with an extremely sound introduction to fluid mechanics." The material has been brought up to date in this new edition and, in particular, a new chapter has been included on the dynamics of a compressible fluid.

Training and Opportunities for Women in Engineering. Verena Holmes and Lesley S. Souter. The Women's Engineering Society. 1958. 41 pp. 3s. 6d. A new edition of "Engineering Training for Women," published in 1955, and at once popular with would-be women engineers and the staffs of girls' schools and women's colleges. Brought up to date to include the many new openings for women since then.

Ultrasonic Inspection of Turbine and Compressor Rotor Blades for Cracks and Other Flaws. J. G. Rasmussen. Dansk Ingemiorforening, Copenhagen. 1958. 12 pp. A reprint of a paper from Ingeniren—International Edition of January 1958.

Reports

AERODYNAMICS

BOUNDARY LAYER—*see* COMPRESSIBLE FLOW

COMPRESSIBLE FLOW—*see also* LOADS
TESTING AND INSTRUMENTS

Some methods of evaluating imperfect gas effects in aerodynamic problems. G. A. Bird. C.P. 397. 1958.
Simple numerical and graphical procedures are described for the calculation of the imperfect gas effects on the properties of steady and unsteady one-dimensional isentropic flows, the Prandtl-Meyer expansion round a corner and normal and oblique shock waves. Both thermal and caloric imperfections are taken into account but relaxation time effects are neglected.—(1.2.3).

Real gas effects on shock-tube performance at high shock strengths. J. L. Stollery. C.P. 403. 1958.
Calculations have been made to find the flow conditions behind shock waves in argon-free air of strengths $M_s = U/a_1$ up to about 35. The tables used are based on the currently accepted value for the dissociation energy of nitrogen of 9·758 e.v. per molecule, and are for equilbrium conditions. The driving conditions needed to produce such strong shocks have been calculated assuming "ideal" hydrogen ($\gamma = 1{\cdot}41$) to be the driving gas. The test conditions available through expanding the flow behind the shock are presented for an expansion ratio of 225 and the question of flight simulation is discussed.—(1.2.3.2 × 1.12.1.3).

Experiments on two-dimensional base flow at $M = 2{\cdot}4$. L. Fuller and J. Reid. R. & M. 3064. 1958.
The afterbodies tested were of constant length with boat-tail angles of 0, 2½, 5, 7½ and 10 degrees. The inside of the model, which was hollow, was shaped in the form of a plenum chamber tapering towards the rear to a two-dimensional convergent nozzle with a parallel throat exhausting into the region behind the base. Measurements were made of the afterbody pressure distribution, the base pressure, and the velocity distribution in the wake for each member of the family over a range of internal flow.—(1.2.3.1).

The exact flow behind a yawed conical shock. G. Radhakrishnan. CoA Report 116. *April* 1958.
A simple numerical method of solving the differential equations of motion behind the shock wave is evolved and applied to the case of the flow of a perfect gas behind a conical shock of semi-apex angle 30° yawed at 20° to a free stream of $M = 10$. The shape of the body which would produce such a shock wave is determined. The properties of the flow between the shock wave and the body surface are investigated particularly with respect to the variation of entropy and the streamline pattern.—(1.2.3.2).

Theory and experiments on supersonic air-to-air ejectors. J. Fabri and J. Paulon. N.A.C.A. T.M. 1410. *September* 1958.
A comparison of experiment with theory is made for air ejectors having cylindrical mixing sections and operating under conditions of supersonic primary flow and either mixed or supersonic régimes of mixing. The effect on ejector performance of such parameters as mixer length and cross section, terminating diffuser, primary Mach number, and primary nozzle position is presented in terms of mass flow and pressure ratio.—(1.2.3.1 × 1.5.1).

Second-order slender-body theory—Axisymmetric flow. M. D. Van Dyke. N.A.C.A. T.N. 4281. *September* 1958.
Slender-body theory for subsonic and supersonic flow past bodies of revolution is extended to a second approximation. Methods are developed for handling the difficulties that arise at round ends. Comparison is made with experiment and with other theories for several simple shapes.—(1.2.0.1).

Compressible laminar flow and heat transfer about a rotating isothermal disk. S. Ostrach and P. R. Thornton. N.A.C.A. T.N. 4320. *August* 1958.—(1.2.1.1 × 1.9.1 × 1.5.4.1).

A nonlinear theory for predicting the effects of unsteady laminar, turbulent, or transitional boundary layers on the attenuation of shock waves in a shock tube with experimental comparison. R. L. Trimpi and N. B. Cohen. N.A.C.A. T.N. 4347. *September* 1958.
The linearised attenuation theory of N.A.C.A. Technical Note 3375 is modified in the following manner: (*a*) an unsteady compressible local skin-friction coefficient is employed rather than the equivalent steady-flow incompressible coefficient; (*b*) a nonlinear approach is used to permit application of the theory to large attenuations; and (*c*) transition effects are considered. Curves are presented for predicting attenuation for a shock pressure ratio up to 20 and a range of shock-tube Reynolds numbers.—(1.2.3.2 × 1.1.2.4 × 1.12.1.3).

Supersonic wave interference affecting stability. E. S. Love. N.A.C.A. T.N. 4358. *September* 1958.
Some of the significant interference fields that may affect stability of aircraft at supersonic speeds are summarised. Illustrations and calculations are presented to indicate the importance of interference fields created by wings, bodies, wing-body combinations, jets, and nacelles.—(1.2.3.2 × 1.8).

CONTROL SURFACES—*see also* STABILITY AND CONTROL
AEROELASTICITY

Exploratory wind-tunnel investigations at high subsonic and transonic speeds of jet flaps on unswept rectangular wings. V. E. Lockwood and R. D. Volger. N.A.C.A. T.N. 4353. *August* 1958.
The investigation was conducted on an unswept rectangular N.A.C.A. 65A006 wing with an aspect ratio of 3·33 and a thicker wing of the same plan form which were modified at the trailing edges to provide several jet-flap configurations. Most of the data were obtained at an angle of attack of 0°. Lift, drag, and pitching-moment data are presented.—(1.3.4 × 1.10.2.2 × 1.8.2.2).

FLUID DYNAMICS—*see also* INTERNAL FLOW
THERMO-AERODYNAMICS

Contribution a l'analyse de la turbulence associée a des vitesses moyennes. A. Craya. Pubs. Sc. et Tech. 345. 1958. (*In French*).—(1.4.2).

INTERNAL FLOW—*see also* COMPRESSIBLE FLOW

A case of longitudinal stick-free dynamic instability of an aircraft fitted with power-operated control, g-restrictor and spring feel. S. Neumark et al. *R. and M.* 3094. 1958.
Following flight experience of a particular aircraft, the effect of including a bob-weight and feel spring in the circuit of a power-operated longitudinal control on the dynamic stability of the aircraft is investigated. The main investigation was done by means of the usual mathematical analysis, with friction represented by an equivalent viscous damping. Additional results are obtained by the use of the Nyquist presentation and of the Philbrick Electronic Analog Computer.—(1.5.2.1).

On fully developed channel flows: some solutions and limitations, and effects of compressibility, variable properties, and body forces. S. H. Maslen. N.A.C.A. T.N. 4319. *September* 1958.
Limitations on fully developed laminar flows due to compressibility and property variations are examined. The cases, for liquids and for gases, wherein such motions are "exact" are determined and solutions are given. For more general conditions, not permitting an exact fully developed flow, limitations are set.—(1.5.1.1 × 1.9.1 × 1.4).

Performance at low speeds of compressor rotors having low-cambered N.A.C.A. 65-series blades with high inlet angles and low solidities. J. C. Emery and P. W. Howard. N.A.C.A. T.N. 4344. *August* 1958.
Tests were made on three blades at solidities of 0·5, 0·75 and 1·0, without guide vanes or stators, over ranges of blade-setting angles and quantity-flow rates. The performance measured in these tests is compared with performance estimated from two-dimensional cascade data for the purpose of extending the correlation of cascade and compressor-rotor data over a range of high-inlet-angle conditions.—(1.5.2.1 × 1.5.4.2).

Prüfstände zur Messung der Druckverteilung an rotierenden Schaufeln. K. Leist and W. Dettmering Forsch. W u VM Nordrhein-Westfalen. No. 422. *(In German).*—(1.5.3.1).

LOADS—*see also* STABILITY AND CONTROL

Critical flight conditions and loads resulting from inertia cross-coupling and aerodynamic stability deficiencies. W. J. G. Pinsker. C.P. 404. 1958.
The effects of the gyroscopic forces on aircraft with large inertias during rolling manoeuvres are discussed and criteria given for the three resulting divergent flight conditions: yaw divergence, pitch divergence and autorotational rolling. The critical loading cases in practical rolling manoeuvres are discussed and methods for the determination of peak loads outlined. Aircraft responses in inadvertent pitch up are analysed and data are given for the estimation of peak loads both for uncontrolled conditions and for pitch up with pilot's counteraction. The principal causes for loss of directional stability are indicated and possible dangerous flight conditions are outlined.—(1.6.2 × 1.8.0.1 × 33.1.1).

Method for calculating the aerodynamic loading on an oscillating finite wing in subsonic and sonic flow. H. L. Runyan and D. S. Woolston. N.A.C.A. Report 1322. 1957.
A method is presented for calculating the loading on a finite wing oscillating in subsonic or sonic flow. The method is applicable to any plan form and may be used for determining the loading on deformed wings. The procedure is approximate and requires a numerical integration over the wing surface. —(1.6.3 × 1.10.1.2).

Experimental measurements of the effects of airplane motions on wing and tail angles of attack of a swept-wing bomber in rough air. J. N. Engel. N.A.C.A. T.N. 4307. *August* 1958.
Flight-test data obtained from an aeroplane at an altitude of 5,000 ft. are analysed to determine the effects of aeroplane vertical translation and pitching motions. Power-spectral techniques are used in order to determine the contributions of these motions to the angles of attack of the wing and tail at various frequencies, and these results are compared with the direct gust-induced angle of attack.—(1.6.3).

Force and pressure measurements at transonic speeds for several bodies having elliptical cross sections. J. B. McDevitt and R. A. Taylor. N.A.C.A. T.N. 4362. *September* 1958.
The measured forces and static-pressure distributions at the body surface and in the surrounding flow field are presented. All of the bodies had an axial distribution of cross-sectional area equal to that for a parabolic-arc body of revolution having a fineness ratio of 12.—(1.6.1 × 1.2.2).

The practical calculation of the load distribution on aircraft. G. Schepisi. AGARD Report 110. *May* 1957.
The mass forces are first derived in terms of the rigid and elastic degrees of freedom, using the dynamical equations. These are solved for symmetrical steady flight, and an outline of the earlier method is given. The solution is attempted for unsteady flight.—(1.6 × 2 × 33.1.1).

STABILITY AND CONTROL—*see also* COMPRESSIBLE FLOW
CONTROL SURFACES
LOADS

Wing flow measurements of the damping in pitch derivative of a 45° *delta wing-body combination and with a tailplane in two positions. R. Rose. C.P.* 402. 1958.
Measurements of the damping in pitch derivative of a 45° delta wing-body combination and with a tailplane in two positions were made at transonic speeds using the wing flow technique.—(1.8.2.2).

Some factors affecting the variation of pitching moment with sideslip of aircraft configurations. E. C. Polhamus. N.A.C.A. T.N. 4016. *August* 1958.
A brief study of available wind-tunnel data with regard to the variation of pitching-moment coefficient with sideslip angle is presented. The effects of such factors as wing plan form, wing-body interference, and tail location are illustrated and discussed, and regions where additional data are needed are indicated.—(1.8.2.1).

Approximate method for calculating motions in angles of attack and sideslip due to step pitching- and yawing-moment inputs during steady roll. M. T. Moul and T. R. Brennan. N.A.C.A. T.N. 4346. *September* 1958.
A method is presented for calculating aeroplane response in a steady roll to pitching- and yawing-moment inputs which approximates the complete four-degree-of-freedom steady-roll response by neglecting the high-frequency mode and simplifying the remaining modal coefficients.—(1.8.0.1 × 1.6.2).

Static longitudinal and lateral stability characteristics at low speed of 60° *sweptback-midwing models having wings with an aspect ratio of* 2, 4 *or* 6. *W. D. Wolhart and D. F. Thomas. N.A.C.A. T.N.* 4397. *September* 1958.
An experimental investigation was performed to determine the contribution of the various components and combinations of components to the static longitudinal and lateral stability characteristics. Emphasis is placed on the directional stability characteristics.—(1.8.0.2 × 1.10.2.2).

The effects of an inverse-taper leading-edge flap on the aerodynamic characteristics in pitch of a wing-body combination having an aspect ratio of 3 *and* 45° *of sweepback at Mach numbers to* 0·92. *F. A. Demele and K. H. Powell. N.A.C.A. T.N.* 4366. *August* 1958.
An investigation has been conducted to determine the effectiveness of a leading-edge flap in improving primarily the drag characteristics of a swept-wing-body combination. Aerodynamic data were obtained for flap angles to 16° over a Mach number range of 0·25 to 0·92.—(1.8.2.2 × 1.3.4).

Effects of frequency and amplitude on the yawing derivatives of triangular, swept, and unswept wings and of a triangular-wing-fuselage combination with and without a triangular tail performing sinusoidal yawing oscillations. W. Letko and H. S. Fletcher. N.A.C.A. T.N. 4390. *September* 1958.—(1.8.1.2).

Investigation of downwash, sidewash, and Mach number distribution behind a rectangular wing at a Mach number of 2·41. *D. Adamson and W. B. Boatright. N.A.C.A. Report* 1340. 1957.
An investigation of the nature of the flow field behind a rectangular circular-arc wing at a Mach number of 2·41 has been made. Pitot and static pressure measurements in the flow field behind the wing and detailed Pitot surveys throughout the viscous wake were made. The flow direction was measured by means of a weathercocking vane. Theoretical calculations of both sidewash and downwash using Lagerstrom's superposition method are compared with experiment. —(1.8.2.1 × 1.10.2.2).

THERMO-AERODYNAMICS—*see also* COMPRESSIBLE FLOW
INTERNAL FLOW
TESTING AND INSTRUMENTS

The effect of free-stream turbulence on heat transfer from a flat plate. S. Sugawara et al. N.A.C.A. T.M. 1441. *September* 1958.
Turbulence was generated by using screens, and the turbulence percentage was measured by a hot-wire anemometer both in the boundary layer and the free stream. The local heat-transfer coefficients was measured at 12 locations along the plate for the cases of various turbulence levels.—(1.9.1 × 1.4.2).

Transient temperature distribution in a two-component semi-infinite composite slab of arbitrary materials subjected to aerodynamic heating with a discontinuous change in equilibrium temperature or heat-transfer coefficient. R. L. Trimpi and R. A. Jones. N.A.C.A. T.N. 4308. *September* 1958.
A solution is obtained in the form of an infinite analytic series and the first six terms of the series are evaluated numerically and tabulated in a form to permit easy computation of heat-transfer problems typical to aerodynamic testing.—(1.9.2 × 33.2.4.0.9).

Mass transfer cooling near the stagnation point. L. Roberts. N.A.C.A. T.N. 4391. *September* 1958.
A simplified analysis is made of mass transfer cooling—that is, injection of a foreign gas—near the stagnation point for two-dimensional and axisymmetric bodies. The reduction in heat transfer is given in terms of the properties of the coolant gas. —(1.9).

A theoretical study of stagnation-point ablation. L. Roberts. N.A.C.A. T.N. 4392. *September* 1958.
A simplified analysis is made of ablation cooling near the stagnation point of a two-dimensional or axisymmetric body which occurs as the body vaporises directly from the solid state. The automatic shielding mechanism is discussed and the important thermal properties required by a good ablation material are given.—(1.9).

WINGS AND AEROFOILS—*see also* CONTROL SURFACES
LOADS
STABILITY AND CONTROL
HELICOPTER AERODYNAMICS

Numerical aspects of unsteady lifting-surface theory at supersonic speeds. H. C. Garner. C.P. 398. 1958.—(1.10.1.2).

An experimental investigation of leading-edge flow separation from a 4 per cent thick two-dimensional biconvex aerofoil. B. D. Henshall. R. & M. 3091. 1958.
The development of leading-edge flow separation as incidence is raised, for a 4 per cent thick two-dimensional biconvex aerofoil, was studied experimentally for wide ranges of incidence at Mach numbers of 0·40, 0·50, 0·60 and 0·70. Pressure distributions and flow photographs are presented which illustrate the growth of the "bubble" of separated flow.—(1.10.2.1).

The flow over delta wings at low speeds with leading edge separation. D. J. Marsden et al. *CoA Report* 114. *February* 1958.
A low speed investigation of the flow over a 40° apex angle delta wing with sharp leading edges has been made to ascertain details of the flow in the viscous region near the leading edge of the suction surface of the wing. A physical picture of the flow was obtained from the surface flow and a smoke technique of flow visualisation, combined with detailed measurements of total head, dynamic pressure, flow directions and vortex core positions in the flow above the wing. Surface pressure distributions were also measured and integrated to give normal force coefficients.—(1.10.2.2).

Investigation of minimum drag and maximum lift-drag ratios of several wing-body combinations including a cambered triangular wing at low Reynolds numbers and at supersonic speeds. C. E. Brown and L. K. Hargrave. N.A.C.A. T.N. 4020. *September* 1958.
Theoretical and experimental data for wing-body combinations with wings of triangular, arrow, and diamond plan form are presented for Mach numbers of 1·62, 1·93, and 2·41 and a Reynolds number range of $1{\cdot}4\times10^6$ to $0{\cdot}7\times10^6$. Included are two each of triangular and arrow plan form wings cambered for approximately uniform load at $M=1{\cdot}62$ and lift coefficients of 0·08 and 0·20. Liquid film studies of the flow over the various configurations are also presented.—(1.10.2.2).

HELICOPTER AERODYNAMICS—*see also* REFERENCE LITERATURE

Effects of compressibility on rotor hovering performance and synthesized blade-section characteristics derived from measured rotor performance of blades having N.A.C.A. 0015 *airfoil tip sections. J. P. Shivers and P. J. Carpenter. N.A.C.A. T.N.* 4356. *September* 1958.
An investigation has been conducted at the Langley helicopter test tower to determine the low tip Mach number blade maximum mean lift coefficient and high tip Mach number compressibility effects. Synthesised rotor blade section-lift and profile drag coefficient data derived from experimental data are presented and compared with previously obtained two-dimensional data.—(1.11.3).

Lift and profile-drag characteristics of an N.A.C.A. 0012 *airfoil section as derived from measured helicopter-rotor hovering performance. P. J. Carpenter. N.A.C.A. T.N.* 4357. *September* 1958.
Rotor hovering performance from which the major portion of the synthesised data were derived is presented for tip Mach numbers from 0·28 to 0·70.—(1.11.3 × 1.10.2.1).

Steuerung und Stabilität von Drehflügelflugzeugen. W. Just. DSH Bericht 4. 1957. (*In German.*)
A comprehensive report on the control and stability of rotary wing aircraft.—(1.11.2).

TESTING AND INSTRUMENTS—*see also* COMPRESSIBLE FLOW

Automatic data reduction equipment for wind tunnels. G. C. Rowley. C.P. 399. 1958.
The developments since 1947 in the data recording equipment used in R.A.E. wind tunnels are reviewed. The latest equipment is described in detail with Appendices of operating instructions.—(1.12.1 × 18).

A Mach 4 *rocket-powered supersonic tunnel using ammonia-oxygen as working fluid. R. W. Graham et al. N.A.C.A. T.N.* 4325. *September* 1958.
To simulate the high heating rates encountered in hypersonic flow, the exhaust gases from an ammonia-oxygen rocket have been used to power a supersonic tunnel. A gas temperature of 4,500°R at $M=4$ was produced in the 15 in. test section of the tunnel. Physical, transport, and one-dimensional aerodynamic data for combustion products of ammonia and oxygen are included.—(1.12.1.3 × 1.9.1 × 27.3).

Notes on wind tunnel pressure measurements from operator's point of view. J. S. Thompson and D. W. Holder. AGARD Report 164. *March* 1958.
A brief description of the objects of pressure measurements in wind tunnels is given, explaining the various purposes for which they are needed and the special requirements of each. Eleven Appendices give an assessment of the accuracy desirable for various applications.—(1.12.1).

Development of pressure measuring devices for a blow-down wind tunnel at the D.V.L. A. Heyser. AGARD Report 165. *March* 1958.
Measuring devices discussed include electronic multimanometers and a miniature differential pressure transducer, as well as intrumentation for the measurement of stagnation pressure. Consideration is also given to the question of response times.—(1.12.5).

A survey of new developments in pressure measuring techniques in the N.A.C.A. J. Dimeff. AGARD Report 166. *March* 1958.
Several transducers designed to meet the particular needs of research within the N.A.C.A. are described: an inexpensive strain gauge transducer with an accuracy of 0·05 per cent of its full differential range; a deflecting diaphragm capacitance type transducer for the range below several millimeters of mercury; a transducer $\frac{1}{4}$ in. in diameter and an experimental transducer in which the deforming member is a thin layer of dielectric compressed under the action of the unknown pressure.—(1.12.5).

Depouillement automatique des mesures de pression en soufflerie. R. Moreau. AGARD Report 167. *March* 1958. (*In French.*)
An investigation resulting in the automatic performance of certain measurement operations in the particular case of wind tunnel pressure measurements is described, notably the elimination, as far as possible, of the human factor in the chain of operations between the multimanometer and the punched card. After a general and detailed statement of the basic principle of the solution found, the automatic handling equipment developed by O.N.E.R.A. is described, and its performance and use indicated. The use of this apparatus for interpreting the data provided by the graphs is assessed.—(1.12.1).

Propulsion wind tunnel digital pressure system. R. W. Kaisner. AGARD Report 168. *March* 1958.
The digital pressure system of the Propulsion Wind Tunnel at the Arnold Engineering Development Center, Air Research and Development Command, U.S.A.F., is described. This system is capable of measuring four reference pressures and 250 model pressures at a rate of 20 per second. Operating modes and reliability of the system are discussed.—(1.12.5).

Manometre a tres large bande de frequence applications aux mesures de pressions rapidement variables. P. Lienard. AGARD Report 170. *March* 1958. (*In French.*)
The characteristics required for the manometers made, the basis on which measurements are performed, the instruments produced and their applications are briefly described, and a short reference to the probable development of methods for the dynamic calibration of the manometers in question is given.—(1.12.5).

Capteurs de pression et manometres miniatures utilisables en soufflerie et en vol. M. Bassière. AGARD Report 173. *March* 1958. *(In French.)*
It is shown how the requirements for wind tunnel and flight pressure measurements have been met by the O.N.E.R.A. in various specific cases. A description is given, together with the performance, of the small instruments developed for this purpose. Methods for the dynamic calibration of manometers are discussed.—(1.12.5).

Pressure measurement in armament research. A. J. Cable. AGARD Report 177. *March* 1958.
Some typical pressure transducers are described (copper-crusher gauges, piezo-electric transducers and strain-gauge transducers) which have been developed and used at A.R.D.E. for internal ballistics research. A quartz piezo-electric transducer and a modified piston type strain-gauge transducer are being used for pressure measurements in the A.R.D.E. hypersonic wind tunnels.—(1.12.5).

Shock tubes. Part I. Theory and performance of simple shock tubes. I. I. Glass. UTIA Review No. 12. *Part I. May* 1958.
An account is given of flows and wave interactions in simple shock tubes. Tables and graphs are presented for the use in the determination of flow quantities in perfect and imperfect inviscid gases. Flow deviations induced by viscosity and heat transfer are considered. A comparison is made of predicted and observed flows including effects produced by the non-stationary boundary layer.—(1.12.1.3 × 1.2.3.2).

Shock tubes. Part II. Production of strong shock waves: shock tube applications, design, and instrumentation. J. G. Hall. UTIA Review No. 12. *Part II. May* 1958.
The coverage is as follows: Sec. 4. Production of strong shocks, including limits of the simple shock tube, electrical and combustion heating, multiple diaphragms, cross-section area change, performance comparison for various drives, explosive and magnetic drives, strong-shock attenuation; Sec. 5. Shock tube applications, including use as a sub- to supersonic wind tunnel, hypersonic shock and gun tunnels, aerophysics research, chemical research, instrument calibration; Sec. 6. Shock-tube materials, design, and construction, including diaphragm technique, pressure and vacuum technique, shock-tube hazards; Sec. 7. Shock-tube flow measurement and instrumentation.—(1.12.1.3).

Properties of impact pressure probes in free molecule flow. E. L. Harris and G. N. Patterson. UTIA Report 52. *April* 1958.
An expression has been derived for the mass flow through a circular tube in free molecule flow when the tube and gas are in relative motion. The gas entering the tube is assumed to have a Maxwellian distribution function and the molecular reflection process at the wall is assumed to be diffuse. The theory has been used to determine the pressure read by an impact probe in free molecule flow. An experimental check of the theory has been carried out using impact probes in a whirling arm apparatus and in the UTIA low density wind tunnel.—(1.12.5).

AEROELASTICITY

See also—AERODYNAMICS—LOADS

Calculation of flutter derivatives for wings of general plan-form. D. E. Lehrian. R. & M. 2961. 1958.
The vortex-lattice method of calculating flutter derivatives presented is an extension to higher frequencies of the work on stability derivatives reported in R. & M. 2922. The method is a modified form of the scheme outlined in R. & M. 2470 and is suggested as an alternative to the latter method since it gives a simpler routing calculation for wings of general plan form. Derivatives are calculated for the following wings describing plunging and pitching oscillations: *(a)* Delta wings of aspect ratio 1·2 and 3 and with a taper ratio 1/7. *(b)* Arrowhead wing of aspect ratio 1·32 with a taper ratio 7/18 and angle of sweep of 63·4 deg. at quarter-chord.—(2).

On the theory of flutter prevention for wing-flap systems. J. D. C. Crisp. A.R.L. Report S.M. 259. *January* 1958.
The general principles of dynamic balancing, configurational equivalence, modal impedance and energy-balance kinematics in the prevention of control surface flutter are outlined. These are applied to binary wing-flap systems and the comparative behaviour established of configurations specified in terms of wing modes; nodal line location; flap span, chord and spanwise station; and simple flap twisting modes. An example follows of some results of a design study of the wing-torsion aileron flutter behaviour of an unbalanced aileron.—(2 × 1.3).

DESIGN AND CONSTRUCTION

See also—REFERENCE LITERATURE

Experimental evaluation of low-band-pass landing-gear shock absorber for pulse loadings. E. Schnitzer. N.A.C.A. T.N. 4387. *September* 1958.
An experimental evaluation of the load-reducing capabilities of the low-band-pass shock strut was made by comparison with a fixed-orifice shock strut. An experimental low-band-pass strut was constructed and equipped with a high-pressure wheel and tyre. Taxi runs were made over single and multiple bumps to determine strut pulse rate response and recycling characteristics. A low-pass vibration absorber is also described.—(4.2.2.3 × 18.2 × 33.1).

Vortragsveranstaltung "Hubschrauber" in Stuttgart am 2. *Dezember* 1955 *mit Vorträgen von. H. Focke, W. Just, F. X. Wortmann. DSH Bericht* 24. *(In German.)*—(4.4).

Vortragsveranstaltung in Köln am 4.9.1956 *mit Vorträgen von Hohenemser, Hafner, Derschmidt. DSH Bericht* 27. *(In German.)*—(4.4).

FLIGHT TESTING

See INSTRUMENTS AND EQUIPMENT

HYDRODYNAMICS

*The Comox Torpedo—a Canadian contribution towards hydrofoil development. M. S. Kuhring. N.R.C. Report ME-*210. *June* 1958.
The development problems encountered in producing, during the period July 1943 to March 1944 an expendable 20 ft. hydrofoil craft suitable for smoke laying is described. The craft was capable of operating at speeds up to 40 m.p.h. in seas of 6 to 9 ft. in height. Some suggestions for further study are given.—(17.1).

INSTRUMENTS AND EQUIPMENT

See also—AERODYNAMICS—TESTING AND INSTRUMENTS
DESIGN AND CONSTRUCTION

Development and flight tests of an instrument flight director for helicopters. P. Brotherhood. C.P. 390. 1958.
The development and flight testing of an instrument system which enables the pilot to fly a helicopter in instrument flight conditions with considerably less concentration or fatigue compared with that required using previous instruments, is described. This instrument, which is intended to replace the present inadequate artificial horizon, gives longitudinal and lateral indications derived from the appropriate mixing of signals from angular displacement of the helicopter, rate of change of angular displacement and control position.—(18 × 13.2).

MATERIALS

See also—FATIGUE

Influence of hot-working conditions on high-temperature properties of a heat-resistant alloy. J. F. Ewing and J. W. Freeman. N.A.C.A. Report 1341. 1957. *(Supersedes N.A.C.A. T.N.* 3727.)
A study was made to determine the influence of various hot-working conditions on the high-temperature properties of a heat-resistant alloy. The effects of hot-working on response to subsequent heat treatment were also studied. The working conditions varied were temperature and amount of reduction. The evaluation of the effects of rolling was based on rupture and creep tests, hardness measurements, microstructural examination, and lattice-parameter measurements.—(21.2.1).

A phenomenological theory for the transient creep of metals at elevated temperatures. E. Z. Stowell. N.A.C.A. T.N. 4396. *September* 1958.
In this theory, a metal consisting of two phases, each with its own elasticity and viscosity, will exhibit transient creep after application of a constant stress. A comparison of the transient creep curves resulting from this theory with experimental data on four different metals shows that the entire family of creep curves for any one metal are given by the theory using a single set of constants appropriate to that metal.—(21.1).

POWER PLANTS

See also—AERODYNAMICS—TESTING AND INSTRUMENTS

Method for determining the need to rework or replace compressor rotor blades damaged by foreign objects. A. Kaufman. N.A.C.A. T.N. 4324. *September* 1958.
This method includes the effects of the location and depth of damage, the material fatigue strength and notch sensitivity, and the maximum-vibratory-stress level of the blade in engine operation. The method was compared with experimental results from fatigue tests of blades edge-nicked in the laboratory. The amount of strength restored by reworking the damaged area was also investigated.—(27.1).

PROPELLERS

Effect of advance ratio on flight performance of a modified supersonic propeller. J. B. Hammack and T. C. O'Bryan. N.A.C.A. T.N. 4389. *September* 1958.—(29.6).

REFERENCE LITERATURE

Literaturverzeichnis des Hubschrauberwesens. W. Just. DHS Bericht 6. *(Bibliography on helicopters.)*—(30.1 × 4.4 × 1.11).

FATIGUE

Cumulative fatigue damage at elevated temperature. W. K. Rey. N.A.C.A. T.N. 4284. *September* 1958.
A study of cumulative fatigue damage at elevated temperatures was conducted using heat-treated SAE 4130 alloy steel. Two-step, three-step, and five-step cumulative-damage fatigue tests were conducted on rotating-beam fatigue specimens at room temperature, 400°F, and 800°F. The results of the tests are compared with those of a theoretical analysis.—(31.2.2.2).

The rate of fatigue-crack propagation in two aluminum alloys. A. J. McEvily and W. Illg. N.A.C.A. T.N. 4394. *September* 1958.
A general method has been developed for the determination of fatigue-crack propagation rates. To provide a check on the theoretical predictions and to evaluate certain empirical constants appearing in the expression for the rate of fatigue crack propagation, an extensive series of tests has been conducted. Good agreement between the results and predictions was found. —(31.2.2.3.2.1.6 × 21.2.2 × 33.2.4.13.10).

Some proposals for evaluating fatigue properties of airplane structures. Bo K. O. Lundberg. F.F.A. Report 76. 1958.
The important proposals are a definition of a Unit Load-Spectrum Period and the expression of spectrum fatigue life in terms of a Spectrum Life Multiple, defined as the number of times that the unit spectrum period is repeated. Methods for direct determination of the parameters of the *S-N* equation are given. A three-parameter equation for spectrum fatigue life is further proposed and theoretical relationships between the parameters of the two equations are deduced. With respect to safety the concept of a "Limit Fatigue Factor" is proposed as distinct from safety factors covering scatter. Designing to a certain low failure rate is further advocated as a method applicable for all types of design.—(31.3.1).

STRUCTURES

LOADS—*see* AERODYNAMICS—LOADS
DESIGN AND CONSTRUCTION

THEORY AND ANALYSIS—*see also* AERODYNAMICS—THERMO-AERODYNAMICS
FATIGUE

The influence of frame pitch and stiffness on the stress distribution in pressurised cylinders. D. S. Houghton. CoA Note 79. *February* 1958.
An analysis is made of the stresses occurring in stringer reinforced cylinders due to the restraining action of the frames. Graphs are presented showing the effect of variation in frame pitch and stiffness, on the bending moment and shear force in the skins, and the hoop stress in the skins between frames. The results are used to show how the optimum structural geometry can be chosen for any given stress ratios.—(33.2.4.3).

Optimum design of a multicell box subjected to a given bending moment and temperature distribution. D. J. Johns. CoA Note 82. *April* 1958.
The optimum geometry of a multicell box of given depth, under a given bending moment and temperature distribution, is obtained. The method is general enough to permit the skin thickness to be either specified, *e.g.* by stiffness requirements, or not.—(33.2.4.1).

Theory of structural design. W. S. Hemp. CoA Report 115. *August* 1958.
The Theory of Structures is for the most part concerned with the calculation of stresses in a given structure under given external conditions of loading and temperature. The real problem is to find that structure which will equilibrate the external loads, without failure or undue deformation, under such conditions of temperature as may be appropriate, and which at the same time will have the least possible weight. The solution of this general design problem is obviously difficult. However, on the basis of certain classical theorems one can make certain progress. This paper reviews the classical results and their current application, develops the mathematical theory for the two-dimensional case and derives a number of special solutions.—(33.2.4.0).

The effective width of plywood flanges in stressed skin construction. H. Tottenham. Timber Dev. Assoc. Res. Report E/RR/3. March 1958.
The determination of the effective width of plywood flanges in stressed skin construction is investigated as a problem of plane stress, the plywood is considered to be elastically orthotropic. The effective widths are derived for a semi-infinite (wide) panel and a panel of finite width with edge shear loads. The effect of the geometry of the plywood construction on the effective width is discussed. A design example is included.—(33.2.4.1).

Non-destructive testing of timber helicopter rotor blades. I. D. G. Lee. Timber Dev. Assoc. Test Record E/TR/3. September 1956.
A method for detecting the presence of cracks in a laminated densified wood used in the construction of wooden rotor blades for helicopters is described.—(33.3.2).

Buckling of sandwich cylinders in torsion. H. W. March and E. W. Kuenzi. Forest Products Laboratory Report No. 1840. *Revised January* 1958.
A mathematical analysis leading to the critical stresses that determine the buckling of cylinders of sandwich construction in torsion is presented. The analysis is complete for cylinders of finite length having orthotropic facings and orthotropic cores. Formulae are given for sandwich cylinders of finite and infinite length. Curves are given for buckling coefficients for cylinders with isotropic facings and orthotropic cores, over a wide range of cylinder sizes and material properties.—(33.2.4.3.5).

Compressive buckling curves for sandwich panels with isotropic facings and isotropic or orthotropic cores. C. B. Norris. Forest Products Laboratory Report 1854. *Revised January* 1958.
Curves and formulae for use in computing the buckling of flat panels of sandwich construction under edgewise compressive loads are presented. Included are curves for constructions with isotropic facings and either isotropic or orthotropic cores. —(33.2.4.6.6).

Survey of thermal problems as affecting the structures of high speed aircraft. P. W. Kleeman. A.R.L. Report S.M. 261. *June* 1958.
The important problems arising from the aerodynamic heating of high speed aircraft are summarised. An extensive bibliography is included.—(33.2).

The natural frequencies of vibration of triangular cantilever plates of uniform thickness. P. W. Kleeman. A.R.L. Report S.M. 262. *June* 1958.
Values of the natural frequency parameters for the vibration of triangular cantilever plates with a range of tip angles and sweep-back angles, are calculated by an energy method using an inextensional theory for thin plates. The results provide an approximation to the large deflection problem of triangular cantilever plates. Data are given to enable the stress distribution in the plate to be calculated.—(33.2.4.7.10).

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